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Summary

Research is a cornerstone of economic growth and development. The Federal Government has played a major role in supporting agricultural research for over a century, transforming U.S. agriculture from a resource-based industry to a science-based industry. At the same time, the demands placed on the U.S. agricultural research system are changing. Consumers and taxpayers expect a wider set of issues to be addressed, including consumer health and food safety, environmental protection, and rural quality of life. Another major change in agricultural research within the United States over the past three decades has been the growing importance of the private sector in both funding and conducting agricultural research. This report re-examines the role of the public sector and the Federal Government in agricultural research. Based on this re-examination, three broad conclusions emerge:

- ***Agricultural research continues to be a solid public investment.*** Publicly funded agricultural research aimed at improving productivity has earned an annual rate of return of at least 35 percent. Consumers, farmers, and investors in agricultural industries broadly share these returns. Even with increasing expenditures for research by the private sector, there is no evidence that the return to public research has fallen off. A 35-percent rate of return is higher than returns on conventional investments in the private sector. This high rate of return suggests that further allocation of funds to agricultural research would be generally beneficial to the U.S. economy, even if it meant reducing other investments.

- ***Agricultural research continues to require involvement by the Federal Government.*** Providing effective patent protection for biological innovations is difficult; as a consequence, the private sector generally underinvests in research. Private sector developers have captured as little as 10 to 12 percent (or less) of the economic benefits from improved nonhybrid crop varieties. Where more effective protection exists for intellectual property rights, the public sector has reallocated public funds away from variety development toward fundamental, or pre-technology, research. This reallocation is in the direction economic analysis would recommend because it focuses scarce public sector funding on research that is unlikely to be done by the private sector. State governments have also been important funders of agricultural research. However, States lack the incentive to fund many types of research because the benefits frequently accrue to farmers and consumers outside the State that paid for the research.

- ***The most compelling case for Federal funding is for more basic research, for the development of nonhybrid crop varieties and other technologies where private incentives are weak, and for research that informs public and private decisionmaking.*** The private sector has little incentive to conduct research in certain areas. These areas include basic, or pre-technology, research (such as plant and animal genetics, pathology, and physiology; conservation and development of unimproved germplasm; and soil physics and chemistry) and research that improves public and consumer decisionmaking (such as basic and applied research on agriculture's relationship to water quality; global climate change; soil quality and land degradation; ecosystem loss; human nutrition and diet; and food safety and quality). Increasingly scarce resources for public agricultural research place a greater burden on research administrators to allocate resources to high-priority areas. They must carefully assess public versus private, and Federal versus State, responsibilities in science and technology development. Economic cost-benefit analysis can be a useful tool for identifying high-payoff areas, although assessing prospective benefits of research and nonmarket benefits remains difficult.

A variety of institutions and market incentives support and encourage agricultural research in the United States These range from direct public funding by Federal and State governments to strengthening private ownership rights to new technology to encourage private individuals and firms to invest in research. With the 1980 Stevenson-Wydler Technology Innovation Act and its 1986 amendment, the Technology Transfer Act, new private-public cooperative research efforts were made possible.

Besides the general conclusions above, several specific conclusions relate to public sector research:

- ***Lack of growth in Federal agricultural research expenditures and the requirements of maintenance research constrain the ability of the public agricultural research system to respond to new demands.*** Federal expenditures for agricultural research account for about 60 percent of the total financial support for public agricultural research in the United States. However, these expenditures have not grown in real terms since the mid-1970's. As much as 30 percent of current expenditures are used to maintain current productivity levels.

- ***Institutional changes in the Federal-State partnership in agricultural research are affecting how research priorities are determined, the mission of the land-grant universities, and the distribution of Federal funds among States.*** Federal support for agricultural research at land-grant universities and State agricultural experiment stations increasingly comes as project funding instead of the traditional block grant, or formula-funding, system. In 1994, formula funds accounted for only 30 percent of Federal support for State institutions, down from 61 percent in 1970. Federal agencies other than the USDA administer an increasing share of Federal funds for agricultural research.

- ***Increased reliance on private sources of funding has raised concerns that private industry could exert a disproportionate influence on the public agricultural research agenda.*** Universities and State agricultural experiment stations rely on the private sector for an increasing share of agricultural research funds. In 1994, nearly 20 percent of agricultural research at State institutions was funded by private industry, product sales, or other private donations, up from 14 percent in 1978.

With the growing importance of the private sector, agricultural research is now a shared responsibility of both the public and the private sectors. Judgments about how and where to spend public funds must consider the level and direction of private agricultural research funding. We have found that:

- ***Private R&D tends to be more commercially oriented than public research.*** Private industry spent at least $3.4 billion for food and agricultural research in 1992, compared with $2.9 billion in the public sector. More than 40 percent of private agricultural R&D is for product development research, compared with less than 7 percent of public agricultural research.

- ***Federal R&D policies and regulations affect private research.*** Government policies affect private agricultural research in several ways. Investments in public agricultural research can lead to increased private research, because of new market opportunities created by scientific and technological advances. There is little evidence that public agricultural research crowds out private research. Intellectual property rights encourage private research by allowing an innovative company to capture a greater share of the benefits from research. Regulations can increase the cost of product development and, thus, discourage private investment in research. At the same time, regulations can encourage research on technologies that are more compatible with environmental, food safety, and nutrition goals.

- ***Strengthened ownership rights for intellectual property for biological inventions have increased private incentives for biological research, but these rights have also raised concerns for future scientific progress.*** In 1992, private industry spent $400 million on plant breeding, and nearly $600 million on all agricultural biotechnology research. However, private incentives to conduct pre-technology research, such as the development of elite germplasm, remain weak, and private investment in applied plant breeding remains uneven across commodities. Patenting of biotechnology inventions has raised concerns that monopolies on new technology may slow longrun progress in biological sciences.

- ***New institutional arrangements are being developed to increase public-private collaboration in agricultural research.*** Cooperative Research and Development Agreements (CRADA's) are formal arrangements between Federal laboratories and private companies to jointly develop and commercialize new technologies. The USDA is also working to establish research consortia between public research institutions and private industry.

Existing evidence suggests that the benefits of research spill over beyond the borders of individual countries. U.S. support of international agricultural research helps diffuse technology abroad and makes an important contribution to reducing hunger and malnutrition around the world. It also brings back technologies that directly benefit U.S. agriculture. However, the "free-rider" problem may also limit the incentives for individual countries to support global agricultural research. The broader issues of the ability of the world to feed a growing population and the relationship between U.S. and international agricultural research are important topics for future research.

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Abbreviations

APHIS—Animal and Plant Health Inspection Service

ARS—Agricultural Research Service

CRADA—Cooperative Research and Development Agreement

CRIS—Current Research Information System

CSREES—Cooperative State Research, Education, and Extension Service

EPA—Environmental Protection Agency

ERS—Economic Research Service

ESCOP—Experiment Station Committee on Policy

FDA—Food and Drug Administration

FDCA—Food, Drug, and Cosmetic Act

FIFRA—Federal Insecticide, Fungicide, and Rodenticide Act

FTE—Full-time equivalents

IPR—Intellectual property right

GDP—Gross domestic product

GEM—Genetic Enhancement for Maize

JCFAS—Joint Council for Food and Agricultural Sciences

NCI—National Cancer Institute

NIH—National Institutes of Health

NLEA—National Labeling and Education Act

NRC—National Research Council

NRI—National Research Initiative

NSF—National Science Foundation

OTA—Office of Technology Assessment

PVPA—Plant Variety Protection Act

PVPC—Plant Variety Protection Certificate

R&D—Research and development

SAES—State agricultural experiment station

UPOV—Union for the Protection of New Varieties of Plants

USDA—United States Department of Agriculture

Agricultural Research and Development

Public and Private Investments Under Alternative Markets and Institutions

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Introduction

Federal support for agricultural research and education has a long history. In the 20th century, public investment in agricultural research helped transform U.S. agriculture from a natural-resource-based industry to a science-based industry. As we move into the 21st century, the challenges facing U.S. agriculture are of a significantly different nature than when the public agricultural research system was first established. Society is asking the agricultural research system to address environmental, food safety, and rural quality-of-life issues, in addition to the traditional concerns about food costs and trade competitiveness.

Government supports research because of the “public good” nature of knowledge. This support can be in the form of direct funding or incentives for private research. The Federal Government has funded agricultural research at State universities for more than a century. These funds are increasingly in the form of project support instead of the traditional institutional (formula) grants. As tax dollars for research have become increasingly scarce, State research stations have increased their reliance on direct contributions from the private sector. Universities are also more aggressively patenting and licensing their discoveries.

Public science policy has moved to increase incentives for private agricultural research by strengthening intellectual property rights (IPR’s) for biological inventions. These include protecting plant breeders’ rights for new plant varieties and allowing utility patents for genetically engineered organisms. The use of IPR’s for biological inventions has raised concerns that they could increase industry monopoly power to the point where new agricultural technology benefits only a narrow set of interests and eventually curtails progress in agricultural science. Regulatory policy also affects incentives for private research. Environmental and food safety regulations can significantly raise development costs for new technology and reduce incentives to conduct research. However, these regulations can also help achieve important social goals that market forces alone may undervalue.

Studies have shown that the past public investment in agricultural research has resulted in large economic benefits of at least 35 percent annual rate of return. From society’s point of view, there has been underinvestment in agricultural research. A high (marginal) rate of return implies that additional dollars for agricultural research would result in substantial increases in economic growth, since it would earn a higher return compared with most other investments. As the capacity of the private sector to conduct applied agricultural research increases, the public sector can focus more resources on fundamental, or pre-technology, research. This research is necessary to release the underlying scientific constraints to technological advances. To ensure both continued efficiency and high returns from agricultural research requires close linkages between science-oriented research and technology-oriented research. This may require closer institutional linkages between public and private research.

Agricultural Science Policy in an Affluent Society

Scientific investigation, accompanied by the new knowledge it generates and the foundation it lays for the development of new technologies, is a cornerstone of economic development and human progress. Overall, economic returns to the U.S. public's investments in science and technology have been large. The origins of public support of science were in agriculture. For more than 130 years, the Federal Government has maintained a commitment to advancing agricultural science and education. This Federal commitment has helped transform agriculture from a resource-based industry to a science- and technology-based industry.

The role of public policy and public funding for R&D has recently received increased scrutiny and review, like most Federal spending given attempts to reduce the Federal deficit. Furthermore, the industry of agriculture and the role of agriculture in the economy have changed dramatically since 1862, when the U.S. Department of Agriculture (USDA) was established. At that time, the desirability of public investment in agricultural research was self-evident: agriculture was the occupation of most of the Nation's population. Today, society's interest in agricultural research is more complex and less obvious. The United States went from a largely rural population (where most people were employed directly in farming) to one where only 2 percent of the population are farmers. Moreover, changing consumer demands and new environmental and natural resource problems all affect the role and priorities for public agricultural research. Additionally, changes in the science base of agricultural research and the legal protection afforded to scientific discovery have enhanced the role of the private sector in agricultural research. These factors have important implications for the future of the Federal role in agricultural research.

Federal Science Policy and Agriculture: A Brief History

The concept that science is in the national interest underlies the Federal Government's role in the support of research. The first Federal commitment to science and technology was aimed at providing a scientific basis for the teaching of agriculture. In 1862, Congress passed the Morrill Land Grant College Act, which gave States and U.S. territories land that they could sell to develop colleges that would offer practical instruction in agriculture and the mechanical arts. Agriculture was then the business of the day: half the population lived on farms, and 60 percent of all jobs were connected to agriculture. Furthermore, farmers and farm families had little access to technical education. This legislation established a network of public institutions still known as the "land-grant colleges and universities." Because agricultural professors needed teaching material and a stronger scientific basis for their teachings, Congress passed the Hatch Experiment Station Act in 1887, which created a system of State agricultural experiment stations (SAES's) under the auspices of the land-grant universities. It also authorized the USDA, which was beginning to conduct significant amounts of inhouse agricultural research to channel Federal funding to the SAES's. Later, Congress took further steps to assure that knowledge and technologies developed at the SAES's and the USDA would reach those not enrolled in courses at the colleges. With the passage of the Smith-Lever Act in 1914, Congress created the Cooperative Agricultural Extension Service (a partnership among Federal, State, and county governments). Essentially, the Morrill, Hatch, and Smith-Lever acts were designed to deliver the practical benefits of education and scientific research to U.S. citizens, with the specific aim of improving the economic prospects and quality of life for farmers, farm families, and rural communities.

Agricultural science held a privileged position until World War II. As late as 1940, almost 40 percent of Federal expenditures for R&D ($29.1 million of $74.1 million) went to USDA inhouse and SAES-based research (Mowery and Rosenberg, 1989). No other sector of the economy benefited from the university-based research support granted by the Federal Government, through USDA, to the SAES's. Thus, the SAES's accounted for a large share of all research conducted at universities.

World War II transformed the U.S. R&D system. First, the Federal Government contracted extensive amounts of R&D with private firms. This arrangement significantly shifted federally financed research and technology development, particularly defense-related R&D, into industry. Since World War II, about 75 percent of all Federal R&D funds have gone to the private sector (Mowery and Rosenberg, 1989). Second, the war spawned huge increases in Federal R&D spending. National security concerns were often the principal drivers, including the Korean War, the Soviet launch of the sputnik, the Vietnam War, and the U.S. "energy crisis." Other social issues and priorities also motivated the expansion of Federal R&D investment, including the Great Society programs, environmental concerns, the "war on cancer," and recently, the international competitiveness concerns of U.S. industry and products. Until the late 1970's, the United States spent more on R&D than all other industrialized countries combined (Mowery and Rosenberg, 1989).

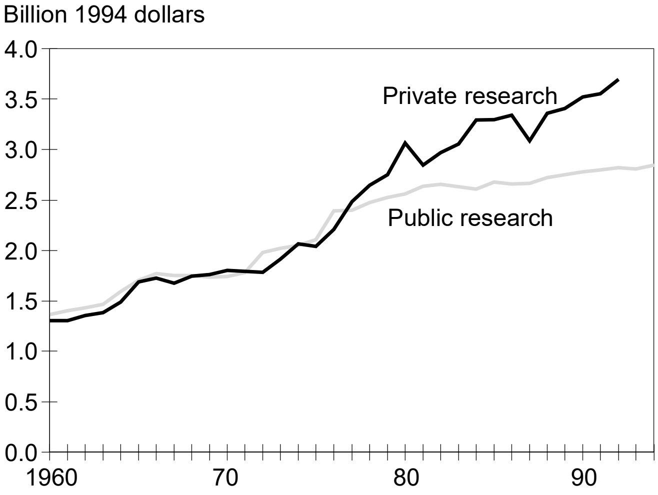
After World War II, other Federal agencies received increasing amounts of Federal science and research funding compared with USDA. Because defense-related research has dominated Federal R&D spending, the Departments of Defense, Energy, and NASA accounted for a very large share of Federal obligations for R&D (about 74 percent in 1991). Also, these agencies account for most Federal R&D funds going to industrial firms. However, university-based research also received a large boost from the opening of the National Science Foundation (NSF) in 1950 and the expansion of the National Institutes of Health (NIH). These agencies greatly expanded Federal support for university science and for the universities' research infrastructure. In 1991, NSF and Health and Human Services together accounted for almost 20 percent of all Federal R&D obligations and over two-thirds of Federal R&D obligations for universities and colleges.

By 1991, USDA expenditures for R&D were less than 2 percent of all Federal R&D spending ($1.2 billion of $61.3 billion). About 4 percent of Federal support for research at universities and colleges was for agriculture ($408 million of $10 billion). Agriculture's future share of Federal resources for science and research may depend on how society judges the benefits of agricultural research compared with other public investments. This requires clear measures of how agricultural science contributes to societal goals such as consumer health and safety, environmental quality, community economic development, and international competitiveness.

The government's role in supporting agricultural research also needs to adapt to the rising involvement by the private sector in conducting agricultural R&D. The post-World War II period has witnessed a significant increase in the private sector's contribution to the development of improved agricultural inputs and food products. Several factors have spurred private industry's interest in agricultural research, including scientific advances in biotechnology, increased market opportunities, and stronger intellectual property rights for biological inventions. Between 1960 and 1992, private spending for food and agricultural research tripled in real terms. Today, the private sector invests more in food and agricultural R&D than do the Federal and State governments combined (fig. 1). However, these raw totals for research expenditures mask a significant shift in emphasis in the type of agricultural research conducted in the private sector. In 1960, the areas of responsibility in research between the public and private sectors were clearly drawn. More than 80 percent of private research was for either improving farm machinery or developing new food products or processing methods. Public research concentrated on increasing yields of crops and livestock. Since then, the private sector has developed significant research capacity in areas that the public sector long dominated, such as plant breeding. By 1992, nearly 60 percent of private research was devoted to increasing crop and livestock yields by supplying farmers with improved crop varieties, agricultural chemicals, animal breeds, feeds, and pharmaceuticals (fig. 2). These trends suggest more potential for overlap between public and private agricultural research. The changing institutional structure of agricultural research in the United States has placed new stresses on the system while also creating new opportunities for technological advance.

Figure 1

Expenditures for agricultural research in the United States, 1960-94[1]



[1] Annual expenditures adjusted for inflation by cost-of-research deflator.

Sources: Economic Research Service. Private research data derived from Klotz, Fuglie, and Pray (1995); public research data derived from U.S. Department of Agriculture, *Inventory of Agricultural Research*.

American Society and Agricultural Science and Technology

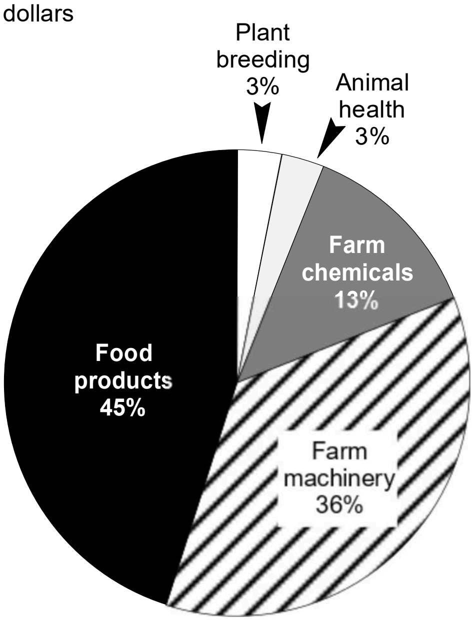
The changing roles of government and private industry in agricultural research partly reflect the changing structure of the American economy. The demands placed on the agricultural research system by farmers and consumers have changed considerably over the past century.

Agricultural Technology and the Needs of a Developing Economy

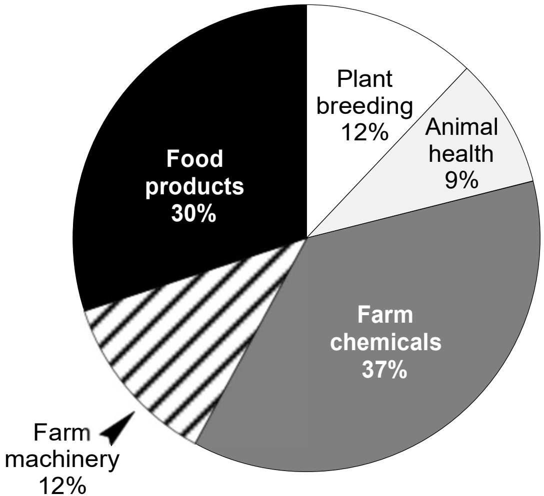
The Federal Government's first commitment to agricultural science came at a time when farming was the

Figure 2
Private agricultural research, by industry

Nominal dollars



1960: $206 million



1992: $3.4 billion

Source: Economic Research Service. Data derived from Klotz, Fuglie, and Pray (1995).

major economic activity in the United States. When the Morrill Act was passed, farmers had little access to formal education to improve their economic status. By the time the 1887 Hatch Act was enacted, the need for a science base to underpin the teaching of agriculture and the development of agricultural technology had been recognized (Cochrane, 1979).

The science of agriculture in these early years was influenced by both supply-side factors (developments in fundamental science to which agricultural scientists had access) and demand-side factors (demand from farmers for improved farming methods and new production inputs that could reduce costs and improve profitability). On the supply side, for example, Justus von Liebig's 1840 book, *Organic Chemistry and Its Application to Agriculture and Physiology*, had a major effect on soil fertilization recommendations (Cochrane, 1979). Also, the rediscovery in 1901 of the Austrian monk Gregor Mendel's work on heredity established the modern science of plant genetics. Early experiment stations also had to recognize the demand side, or technical needs, of their farm constituencies. For example, early biological innovations were often practical, like identifying the most suitable varieties and agronomic practices for growing small grains crops in the Plains States. Nineteenth-century biological innovations also included increasing dairy productivity in the East and Midwest and developing a successful horticultural industry in California (Olmstead and Rhode, 1993). Cochrane writes that, "Perhaps a dozen agricultural experiment stations were doing highly professional work in the agricultural sciences by 1900. Once the scientific properties and relations of plants, animals, and the soil were understood, the technologies for combating plant and animal disease and for increasing yields could begin to flow forth. And they did so after 1900" (Cochrane, 1979, p. 245).

For many decades, economic forces probably were the strongest influences shaping agricultural science and technology in both the public sector (at the experiment stations and USDA) and the private sector. Thus, while science and technology change the face of society, they are simultaneously responding to society's needs. A conceptual framework for examining how economic forces affect the rate and direction of technical change is the induced-innovation model. This model assumes that innovators (who may be farmers, entrepreneurs, or scientists) develop new technologies that conserve increasingly expensive resources and use relatively less expensive ones. In the induced-innovation model, a rise in the price of petroleum-derived energy, for example, would induce the development of more energy-efficient machinery and alternative energy sources.

The induced-innovation model explains why farm mechanization was the first wave of technological change in U.S. agriculture. Mechanization got underway in the 1830's, but surged during 1860-1900. It was spurred first by the manpower shortage on farms during the Civil War, and again when farmland more than doubled as the Nation expanded westward in the late

1800's (Cochrane, 1979). The introduction and expansion of mechanical technology was not meant to increase yields but instead to ease the substitution of power and machinery for relatively expensive labor. Mechanical innovations continued to reduce labor inputs in farming for decades. Labor inputs declined 35 percent between 1948 and 1960, and another 47 percent between 1960 and 1990 (USDA, 1994). Sophisticated soil preparation and planting and harvesting machinery, in combination with the internal combustion engine, removed most of the hard physical labor from farming, reducing the amount of labor in farming to a small fraction of total costs.

The induced-innovation model also helps explain why, following the close of the land frontier in the early 20th century, yield-increasing technologies began to be developed and introduced on a significant scale. Plant breeding was aimed at producing more fertilizer-responsive varieties that were also resistant to drought and diseases. This breeding significantly increased yields per acre of corn in particular, but also for soybean, cotton, wheat, and most other crops. In the post-World War II period, the development and application of biological and chemical technologies intensified. Use of commercial fertilizers increased dramatically during this period, contributing importantly to increases in crop yields. Hayami and Ruttan (1985) argue that declining real energy prices (in relation to land and labor costs) induced the development and widespread adoption of petroleum-based agricultural fertilizers and chemicals.

Animal production technology also improved significantly after World War II. Feed conversion rates in poultry improved dramatically; modern drugs and vaccines effectively curtailed animal disease; and knowledge of animal nutrition improved animal feeding practices (Cochrane, 1979).

Scientific discovery and agricultural technology development have contributed to remarkable increases in farming productivity. From 1948 to 1991, total factor productivity (farm output per unit of total factor input) increased nearly 150 percent (USDA, 1994). Productivity growth in farming, in turn, contributed to the growth of the national economy. This is because more food and fiber could be produced using fewer of the Nation's resources; thus, other sectors could grow more rapidly at less cost. In addition, since farm commodities could be produced more cheaply, food and fiber products could be priced reasonably. Consequently, consumers had more income to spend on other goods and services. In fact, an important indicator of a country's level of economic progress is the portion of its citizens' disposable personal income spent on food. In the United States that portion was slightly above 11 percent in 1992, in contrast to 22 percent as recently as 1949 (Dunham, 1993).

Agricultural science has contributed to both abundant, reasonably priced food for U.S. consumers and making U.S.-grown farm and agricultural products available to people in the rest of the world. Significant percentages of some U.S. commodities are exported. For example, about 60 percent of wheat production and 30 percent of soybean production are exported. Agricultural products compose about 10 percent of all U.S. merchandise exports (Economic Report of the President, 1995). Today, science continues to support the global competitiveness of U.S. agriculture, but it is also increasingly turning its attention to addressing other societal issues related to modern farming.

Demands of an Affluent Society

The U.S. economy has changed dramatically since the early years of public investment in agricultural education and research. Farming now directly accounts for only a small share of national economic output and national employment. This is largely because of the significant achievements of agricultural science. However, if we define agriculture more broadly to include activities beyond the farmgate (such as food and fiber processing, marketing, and retailing), it still accounts for about 18 percent of U.S. jobs and more than 15 percent of the Nation's gross domestic product (*Economic Report of the President*, 1995). Decisionmaking in this huge agribusiness sector is increasingly driven by modern consumer concerns regarding nutrition and health, food safety and quality, convenience, the environment, and even ethical considerations such as animal welfare. The role of agricultural science and technology, and of public policy more generally, in addressing this array of modern-day issues is still evolving.

Many modern consumer demands are well articulated in the marketplace. The market appears to respond readily to demands for more varied, convenient products with desirable sensory attributes like taste and appearance. An excellent example of a market response is the recent development of the U.S. kiwi fruit industry. This industry did not exist until U.S. consumers developed a taste for the fruit after being introduced to kiwis from New Zealand. Another example is the shift of U.S. meat consumption to more poultry and less beef. This shift was based partly on nutrition and health information. It demonstrates how health concerns can drive the composition of products in the marketplace. An increase in market demand for food products with sensory or other easily discernible characteristics can induce firms to develop new products with these attributes.

The market may respond inadequately to other types of consumer preferences. It may, for example, undervalue consumers' demand for environmental goods, nonsensory attributes of food products (like safety and nutrition), and attributes that meet ethical or religious standards. A consumer may be unable to identify these attributes simply by looking at, feeling, smelling, or tasting products. If consumers cannot "vote" for these product characteristics by changing their consumption patterns, then market forces may be unable to drive new product and technology development in a direction that meets these demands. Public policy may be useful in providing the basis for better-informed consumer choices that can then signal food manufacturers and product developers. Examples of such policies are: requiring that certain scientific information be provided through labeling, setting food safety standards, and providing product certification standards (like those for organic produce). Because of relatively weak private incentives, there may be a stronger justification for public investment in agricultural science and alternative technologies directed toward enhancing these "public goods."

Again, the induced-innovation model can be used to explain why technology development may have provided less of these public goods than was optimal from society's point of view. For example, the model can be applied to the development of chemical-intensive farm production technologies. The expansion of the use of agricultural chemicals increased agricultural productivity significantly, as discussed above, but also negatively affected farmworker health, water quality, and wildlife habitat. These negative effects impose costs on society that are not reflected in costs of production borne by farm owners or the market prices of farm products. In other words, the social costs of farm chemical inputs exceed their private costs. Moreover, consumers have become increasingly concerned about these social costs in recent years. Unless the private costs are brought more in line with social values, the induced-innovation model suggests that agricultural research will overemphasize technologies that use chemical inputs and underinvest in technologies that conserve them (Ruttan, 1971).

Besides their environmental concerns related to onfarm chemical use, today's consumers express concern over health risks associated with exposure to chemicals through food consumption. Individual consumers have many different degrees of willingness to accept health risks; in other words, the same detailed knowledge of the health risk may result in different buying habits by different consumers. However, national polls show that most consumers express some form of concern about exposure to chemicals used in producing, storing, and processing foods.

Some modern agricultural technologies, such as biotechnology (especially recombinant DNA), have also generated consumer concerns about their potential health and environmental effects. Biotechnology is being used to develop plants that are more resistant to pests, disease, and herbicides; plants that fix atmospheric nitrogen; plants with the ability to tolerate drought and frost; animals with increased lean muscle tissue and milk production; and microorganisms with improved properties for fermentation in food processing. Agricultural biotechnology is also being used to improve such food quality traits as flavor, texture, shelf life, or nutritional content, and to develop foods with decreased toxins and allergens. These new technologies have tremendous potential benefits. However, concern has been raised about whether agricultural biotechnology products pose added risks to environmental quality and to human health (Reilly, 1989; Caswell, Fuglie, and Klotz, 1994). Increased research and education may be needed to understand these effects more thoroughly.

Sometimes consumer concerns regarding farm production technologies take on social and ethical dimensions. Worker rights and safety and animal welfare are social issues that can result in preferences of some consumers for food products produced in certain ways. For example, some consumers prefer "dolphin-safe" tuna (tuna harvested without the possibility of dolphins being ensnared in the nets) or "free-range" chicken (from poultry raised in less confined conditions). Again, these types of food attributes may be difficult for consumers to detect unless reliable information is available. Therefore the market may undersupply such attributes.

Despite the relative abundance and accessibility of food in the United States and other developed nations, nutrition and diet still strongly affect human health. These linkages are increasingly recognized and studied. Heart disease, cancer, stroke, and diabetes—the four leading causes of death in the United States—have been linked to diet. Proper diet might forestall at least 20 percent of the annual deaths from these four causes (National Research Council, 1989a). Hypertension, osteoporosis, and obesity, which affect productivity and lifespan, are also diet-related. These seven health conditions cost society an estimated $250 billion each year in medical costs and lost productivity (Frazão, 1995).

The food industry is bringing numerous new products to the market. Often, these new products are responses to growing consumer awareness of dietary risks, particularly now that labels allow consumers to assess a product's nutritional content. The private sector may still have relatively little incentive, however, to conduct the research that reveals the underlying links between diet and health.

Environment, food safety, and health risk concerns have provided a particularly difficult set of issues for science research and technology development. The economic benefits of research arise from satisfying consumer demands at the least cost. In the areas of environmental degradation, food safety, and health risk, however, much evidence suggests that consumers' perceptions of risks often vary markedly from scientific assessments (Kramer, 1990; Breyer, 1993). Thus, public research may poorly serve the public interests (at least as evaluated from a scientific perspective) when the research focuses only on consumer demands. The fact that the science is incomplete and uncertain makes the problem more complex. Given the mass of often conflicting information about risk, consumers may have difficulty distinguishing accurate information from false claims. Under such circumstances, they may exhibit skepticism of all claims from the scientific and health communities.

Economics of Science Policy

The changes in consumers' expectations of and farmers' needs from agricultural technology help explain why the U.S. agricultural research system has moved in new directions since the mid-19th century. It also puts into perspective some questions about Federal policy toward agricultural R&D concerning funding levels, research resource management and allocation, the role of intellectual property rights, and the division of labor between public and private research. Economic theory can provide a framework for addressing science and technology policy questions.

A basic economic argument underlying public policy toward science and technology is that the private sector tends to underinvest in research. This is because the inventor can only appropriate the product of research, new knowledge, to a limited extent. Once new knowledge is sold, it is no longer possible for the inventor to continue to sell it because any one purchaser can reproduce the information at little cost (unless the inventor can somehow exclude nonpayers from using the invention).[1] The benefits from research that the inventor cannot capture are called "spillovers." They include benefits to rival firms that can copy the invention or use it to develop new inventions. Spillovers also include benefits to consumers from lower priced or improved products. Since the profitability of research for inventors (private benefits) is smaller than benefits to society (which include the spillovers), profit-oriented individuals and firms will often underinvest in research (Nelson, 1959; Arrow, 1962).

The presence of large spillovers provides an economic rationale for direct public support of research, either through a publicly operated research system or through contracting with private firms. The spillover principle explains why only the largest private corporations invest in significant amounts of basic research, and establishes a clear public role for the support of fundamental science. Large spillovers can also result from applied R&D. Empirical studies show that innovating firms capture only about half the social returns from industrial R&D (Mansfield and others, 1977). Similar results have been found for agricultural R&D conducted by the private sector (Huffman and Evenson, 1993).

Although direct public support of research successfully addresses the spillover problem, public support itself may contribute to other forms of inefficiency. A real world disadvantage of government funding of programs is the lack of incentive for cost control in situations where performance monitoring is difficult. In the private sector, market competition disciplines firms to control costs. Inefficiency resulting from lack of cost control in conducting research may not, however, be a serious problem for the public agricultural research system in the United States. The decentralized nature of the system, in which most research resource allocation decisions are left to the directors of individual State agricultural experiment stations (SAES's), tends to reduce this source of inefficiency. This is because it fosters competition among the States. Ruttan (1980) likens this system to 50 competing firms in a market economy. Nonmonetary rewards, such as professional prestige, also motivate scientists not to waste time and resources.

Perhaps a more serious potential deficiency of public funding of research is the way information is acquired and processed in allocating research resources. Answers to two fundamental questions determine the value of any proposed research project: (1) what is the likelihood that the research project will be successful in making a scientific or technological advance? and (2) supposing the project is successful, what is the value of the scientific or technological advance to society? (Ruttan, 1982). Selecting the best portfolio of research projects requires information on both questions. Judgments about the first question are best provided by the leading scientists in the field. Analysis of the second question requires up-to-date information on market demand, re-

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[1] Knowledge has the two classic characteristics of a public good: non-rivalry (use of knowledge does not reduce the amount available to others) and non-excludability (others cannot be prevented from using knowledge once it is first made available) (Samuelson, 1954). Another reason private firms underinvest in research is that it is often a high-risk undertaking (Arrow, 1962).

source scarcities, and consumer preferences. Wright (1983) argues that when the answers to these questions are complex, research efficiency is enhanced by an R&D system that relies more on private sector entrepreneurs rather than on a public administrator. Encouraging private entrepreneurs to undertake research allows exclusive private information to be incorporated into research decisionmaking and revealed in the marketplace.

Providing intellectual property rights (IPR's) for new inventions is an important policy tool for encouraging the private sector to conduct research. IPR's (such as patents, plant breeders' rights, and trade secrets) allow the inventor to exclude others from making, using, or selling the invention for a limited period. Patents also encourage inventors to publicly disclose their discoveries. Patents are awarded for inventions considered new, useful, and not obvious to an expert in the field. To receive a patent, an inventor must describe the invention in sufficient detail so that someone skilled in the art can reproduce it. The degree of the monopoly afforded by a patent depends on its duration (17-20 years in the United States) and by the breadth of exclusion (as defined by the patent claims) given to the owner. Plant breeders' rights, which extend for 20 years, are awarded for new varieties of crops that are distinct, uniform, and stable. Plant breeders' rights protect only the reproductive material of the plant. State statutes protect trade secrets if they are kept confidential. Trade secrets may be kept out of the public domain indefinitely.

IPR's reduce the spillover problem by enabling the inventor to capture a greater share of the benefits from new technology. In many cases, an inventor (or his licensee) will be unwilling to make the investment necessary to commercialize the invention unless he can be assured of a market for the product. A patent grants such a monopoly, at least for a limited period of time. However, a monopoly also generates welfare losses. This is because a monopolist will generally charge a higher price for a product (and produce less) compared with a competitive market. Therefore, once an invention is commercialized, patents may lower the social value of an invention, although it is preferable to having no invention at all. The tension between these two types of market failure underlies much of the public policy debate about intellectual property rights. How these rights are defined and enforced carries implications for both economic efficiency and equity. Inventors often favor stronger intellectual property rights so that they may obtain the largest possible share of the social benefits of their invention. Consumers and other users of an invention, on the other hand, seek to limit the monopoly power of an IPR in order to increase the availability of the invention and reduce its cost.

Market failure also affects the direction that new technology takes. Since markets are frequently incomplete (that is, market signals, such as prices, may fail fully to convey social values or consumer preferences), private incentives to develop certain technologies are reduced. Prices provide an important indication of resource scarcity and product demand. According to the induced-innovation model, firms respond to these signals by investing in specific, new technologies. To the extent that market signals do not reflect societal interests (such as the demand for environmental amenities or food safety), the private sector will tend to underinvest in technologies that meet these demands. For example, if the social cost of using certain inputs exceeds their private cost, then market incentives will favor the development of technologies that use those resources at the expense of technologies that conserve them (Ruttan, 1971). Another example is food safety and nutrition. Detecting nonsensory attributes of food products is often difficult (sometimes impossible) for consumers. Without a system of safeguards, standards, or information labels, private companies have little incentive to develop products with enhanced nonsensory characteristics (such as higher vitamins, lower fat, or fewer chemical residues). Establishing rules and regulations in the agricultural and food industry is one policy approach to overcome these kinds of market failures. However, the costs of complying with regulations may be greater than the benefits. Regulations can also have unintended effects on market structure.

Although this economic framework provides some general guidelines for public science policy, it gives few prescriptions about the best way to support R&D. Each alternative policy approach, whether to increase direct public funding of research, strengthen IPR's, or correct market imperfections, involves trade-offs among competing objectives. The economic argument for direct public support of research is perhaps clearest for basic research since it has large positive spillovers. This may also include many kinds of applied research and technology development where market incentives do not provide for sufficient private interest. On the other hand, budgetary and managerial constraints limit government support of research. Private companies are more responsive to changing user needs, and market competition disciplines their efficiency. Intellectual property rights, regulations, and other types of market interventions can partially correct for the lack of appropriate market incentives. However, this is often at the cost of generating other kinds of inefficiencies. Determining the appropriate design of science policy requires analysis of the relative size and significance of these trade-offs.

Public Support for Agricultural Research

There are significant new challenges and opportunities for the Federal-State agricultural research system. Public expectations have changed about the future directions for agricultural technology, and a strong private sector capacity in agricultural research has emerged. These trends raise questions concerning the appropriate level of public support for agricultural research and the organization and allocation of resources among competing research goals.

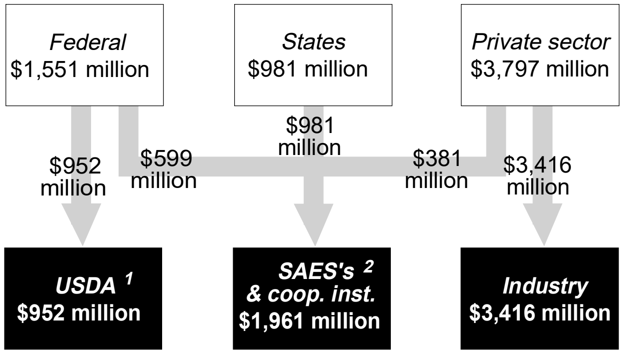
The Federal-State Partnership in Public Agricultural Research

The public system of agricultural research in the United States is based on a Federal-State partnership created in the latter-half of the 19th century. The Federal Government supports intramural research at USDA research agencies (Agricultural Research Service, Forest Service, and Economic Research Service). It also funds extramural research at State institutions (administered by the Cooperative State Research, Education, and Extension Service, or CSREES).[2] The State component is built upon a joint teaching-research-extension mission carried out by the land-grant universities and the SAES's.[3] A combination of Federal, State, and private monies supports the State system.

In 1992, nearly two-thirds of the $1.55 billion spent by the Federal Government for agricultural research went for inhouse research at USDA agencies (fig. 3). The remaining third was distributed to State institutions. State governments allocated $981 million for agricultural research, all going to the State system. The private sector spent more than $3.7 billion on food and agricultural research. Of these funds, $3.4 billion was for research in their own laboratories, and $371 million went to State institutions. Private-sector contributions to the State system include $143 million in direct grants from industry, $116 million for product purchases and patent license fees, and $121 million from other sources (such as grants from nonprofit foundations). In total, the State system received $1.96 billion for agricultural research in 1992. Federal funding for the State system is designed to draw each State into the agricultural research partnership. The Hatch Act accomplishes this by making Federal grants for agricultural research available to a State only if it matches the Federal contribution with its own funds. This effort has clearly been successful; State funding of the SAES system now significantly outweighs the Federal contribution.

Figure 3

Sources and flows of funding for agricultural research in 1992



[1] Includes research by Agricultural Research Service, Forest Service, Economic Research Service, and National Agricultural Library.

[2] SAES's are State agricultural experiment stations; coop. inst. include the 1890 schools, forestry schools, and veterinary schools.

Sources: Economic Research Service. Data for Federal and State research expenditures derived from USDA, *Inventory of Current Research*; data for private sector/industry research expenditures estimated from Klotz, Fuglie, and Pray (1995).

The argument for Federal (in addition to State) funding of the State system rests on the concept of interstate "spillovers." Some portion of the economic benefit from research conducted in a State accrues to the State's own producers and consumers, and some portion "spills over" to consumers and producers in other States. If a State considers only the benefits of its research to its own producers and consumers, it will tend to invest less than what would be optimal from a national perspective. The argument is similar to the case of a private firm underinvesting in research because it cannot capture

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[2] The Cooperative State Research Service and the Cooperative State Extension Service were combined to form CSREES in the 1994 reorganization of the USDA.

[3] Besides the land-grant universities and the SAES's created by the 1862 Morrill Act and the 1887 Hatch Act, other components to this system have been added over time. The "Second Morrill Act" of 1890 established a system of colleges free from racial discrimination, leading to the "1890 Schools." The 1977 Evans-Allen Act provided funds to support agricultural research at these institutions. Federal funds for forestry research were substantially increased in 1962 with the passage of the McIntire-Stennis Act. Section 1433 of the Food and Agriculture Act of 1977 made research funds available for veterinary schools. These Acts, along with the Hatch Act, made block grants available to State research institutions based on a formula that determines the share of Federal dollars going to each State. In this report, the "State system" or "State institutions" refer to State agricultural experiment stations and other cooperating institutions, (such as 1890 schools, forestry schools, veterinary schools, and other academic and private institutions) supported by USDA formula funds.

all the returns. Furthermore, States will tend to favor applied and technology development research at the expense of more basic, or pre-technology research, since the former is likely to have less interstate spillover (see box, "Basic Research, Applied Research, and Technology Development"). Advances in pre-technology research, on the other hand, are likely to spill over to other States' producers. This is because these findings are likely to contribute to the development of production technologies suitable to a range of climatic conditions or even multiple commodities. Empirical analyses support the hypothesis that interstate spillovers from agricultural research are significant (Evenson, 1989).

Besides investing in the States' public research programs, the Federal Government maintains its own inhouse, or intramural, agricultural science expertise (see box, "Federal Support for Intramural versus Extramural Research"). There are at least two key reasons for maintaining a strong intramural research base. One reason is that the effectiveness of the State system depends on regional and interregional coordination and linkages provided through national program leadership in the USDA. For example, Ruttan (1982) argues, "The overlap of Federal support and coordinating services made it possible to give more concentrated attention to specific problems of crop improvement of common importance to several States than would have been possible if researchers in each State had worked in isolation. This involvement with the State experiment stations gave the USDA's research program greater access to basic science capacity in fields such as genetics, entomology, and physiology than could have been assembled with the Federal research system" (p. 78).

The second major reason for intramural research is that there are research problems and issues of national importance that may receive too little attention from

Basic Research, Applied Research, and Technology Development

Research and development (R&D) cover a broad range of investigative activities. The National Science Foundation (NSF) defines "basic research" as research conducted to gain a more complete understanding of the subject under study, without specific applications in mind. The NSF defines "applied research" as research aimed at gaining knowledge to meet a specific, recognized need. "Technology development research" is defined as the systematic use of research knowledge in the production of useful materials, devices, systems, or methods (National Science Foundation, 1993, p. 94). One problem with the NSF definition is that the characterization of a research activity depends on the scientist's interpretation and motivation for the research. What may be basic research to one scientist may be applied research to another.

Huffman and Evenson (1993) developed a structural representation of the R&D system for agriculture. They defined R&D activities as belonging to (1) the general sciences, (2) the pre-technology sciences, or (3) technology invention. Innovations from these activities result in products that can be extended to final users, for example farmers, consumers, and government agencies. Some of the fields of science and technology that characterize these activities are:

General sciences	**Pre-technology sciences**	**Technology invention**
Chemistry	Soil physics and chemistry	Agricultural chemistry
Genetics	Plant and animal genetics	Plant and animal breeding
Biology	Plant and animal pathology	Horticulture
Microbiology	Plant and animal physiology	Agronomy
Zoology	Nutrition	Veterinary medicine
Physics	Engineering	Mechanics
Atmospheric science	Climatology	Irrigation methods
Mathematics	Computer science	Computer software development
Economics	Applied economics	Farm management

General and pre-technology sciences are conducted primarily by universities and public research agencies. The products of this research are too general to be protected by intellectual property laws, and thus these activities attract little private-sector support. Technology invention is the product of both public and private research, and it in some cases public and private technology invention activities may overlap. Many public-sector technology inventions, however, are in fields where the products of research are not marketable and there is inadequate incentive for private invention (Huffman and Evenson, 1993, pp. 42-3).

Federal Support for Intramural versus Extramural Research

Intramural research (USDA)	**Extramural research** (State agricultural experiment stations and other cooperating institutions)
USDA's intramural research agencies include the: ***Agricultural Research Service (ARS)*** ✦ Accounts for about 70 percent of USDA appropriations for intramural research ✦ The workforce is 8,200 full-time equivalents (FTE's), including some 2,600 scientists ***Economic Research Service (ERS)*** ***Forest Service (FS)***	Most extramural agricultural research grants are administered by USDA's Cooperative State Research, Education, and Extension Service (CSREES), which also administers education and extension grants to State institutions. State agricultural experiment stations (SAES's) conduct most extramural agricultural research. SAES scientists are typically members of academic departments of land-grant universities, especially the colleges of agriculture. ✦ SAES staff includes about 24,000 professional and other staff (FTEs), including 6,400 scientist years. Research at forestry and veterinary medicine schools and colleges is also supported by CSREES-administered grants. These programs are also typically at land-grant universities. CSREES-administered grants also support the agricultural research programs of the historically black "1890" land-grant colleges.
Arguments in support: ✦ Provides in-house science expertise, essential for national and international leadership and coordination in agricultural science. ✦ Takes on higher-risk and long-term research, like plant and animal genome programs and global environmental change. ✦ Addresses national and regional research problems where State investment incentives may be low but social payoffs are potentially high, like food safety and diet and health. ✦ Maintains research infrastructure and laboratory capacity that is too expensive for individual States, such as hydrology labs and germplasm operations. ✦ Supports research needs of regulatory agencies, such as APHIS, FSIS, and FGIS, and the development of science-based regulations and policy. ✦ Collaborates in multinational agricultural research partnerships, like germplasm preservation. ✦ Facilitates technology transfer and commercialization by initiating and coordinating government/industry/university consortia.	***Arguments in support:*** ✦ Responds to State and local constituents and addresses specific agroclimatic needs. ✦ Federal grants underwrite and encourage State investments in university research. ✦ Has links to universities' nonagricultural basic and applied research programs. ✦ Federal grants support top scientists and researchers at universities. ✦ Extramural research grants support graduate students and thus human capital development in science. ✦ Research conducted at universities provides frontier material for classroom instruction and thus enhances education.

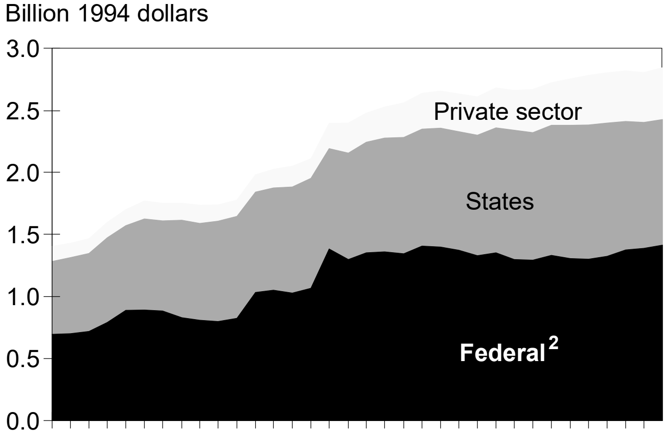
individual States or even regional programs. Food safety, nutrition and health, and germplasm preservation are examples of research issues for which there is a national rather than a State-specific or regional constituency. Federal regulatory agencies may particularly look to the intramural research agencies to provide the science base for the regulatory programs that protect the safety and health of the Nation's consumers.

Finding an administrative structure that would allow USDA's intramural science agencies to address these goals has provided a challenge to Federal research managers. For example, in 1972 USDA decentralized the research program management of USDA's Agricultural Research Service (ARS) from a national to a regional structure. To simplify further coordination with the SAES's, USDA organized ARS research programs around four regions. The reorganization was, however, not without controversy. Some observers felt that it compromised the ability of the USDA to provide national leadership in agricultural research (Office of Technology Assessment, 1981; Ruttan, 1983).

Public research expenditures rose by 3-4 percent per year in real terms up to around 1980, but since then, growth has slowed to 0.7 percent per year (fig. 4). To calculate real (inflation-adjusted) funding trends, annual expenditures are adjusted by a cost-of research index.

Figure 4

Federal, State, and private support for public agricultural research, 1960-94[1]



[1] Annual expenditures adjusted for inflation by cost-of-research deflator.

[2] Includes funds for USDA research agencies (Agricultural Research Service, Economic Research Service, and National Agricultural Library) and cooperative State research.

Source: Economic Research Service. Data derived from Alston and Pardey (1995).

Most of the post-1980 growth has come from increased contributions from the private sector, mainly for research conducted at land-grant universities. In real terms, Federal funding for agricultural research has been stagnant since 1976. State governments continued to increase their support for agricultural research until the economic recession of the early 1990's.

The ability of the public agricultural research system to respond to new demands is constrained by the slow growth in real funding and the substantial resources needed for maintenance research. Maintenance research is needed to offset the tendency of livestock and crop yields to fall over time, due to the emergence of resistant strains of pests and diseases. Requirements for maintenance research increase as agricultural productivity increases (Ruttan, 1983). Some estimates suggest that around 30 percent of agricultural research expenditures go to maintaining current yield levels (Adusei and Norton, 1990; Huffman and Evenson, 1993).

Setting the Research Agenda

Ruttan (1982) characterized the Federal-State agricultural research system as "articulate, decentralized, and undervalued" (p. 249). The institutional, or formula, funding approach established by the Hatch Act created a decentralized management structure. Decisions about allocating research resources were left largely to the States rather than to a central authority. The decentralized structure, with the combined research-extension role of the land-grant universities, enabled farm constituencies to express their needs directly to the scientific establishment. This established articulation among science-oriented research, technology-oriented research, and farm production. It served to direct research resources to commodities and production constraints important to the locality or State. According to Ruttan, these factors contributed to high economic returns to research. Because returns to research remained high, the system may have been undervalued, that is, the investment in public agricultural research may have been too small. The reasoning is that if an investment gives very high returns, its funding should be increased to the point where the return from the investment equals the opportunity cost of the funds. If agricultural research yields a higher return than other types of investment, shifting more funds to agricultural research would increase overall economic efficiency and growth.

While the system was effective in developing and delivering new technologies that increased farm productivity, it has been criticized for being slow to respond to the needs and expectations of other constituencies, such as consumers, nonfarm rural groups, and farm laborers. Internal and external evaluations of the system recommended changes in the way the system was managed and operated. To some extent these recommendations were carried out. Most noticeable is the changing nature of financial support for the system: the relative importance of institutional (formula) funding has fallen substantially, and support from the private sector has grown.

Criticisms of the Public Agricultural Research System

Despite the contribution of public agricultural research to agricultural productivity increases, the system came under increasing pressure during the 1960's and 1970's. Some critics charged that the agricultural research establishment was slow in responding to environmental, distributional, and humanitarian concerns. These critics sought to increase the attention given to such issues as environmental protection, natural resource conservation, human nutrition and health, rural development, the problems of hired workers, and animal welfare. Ruttan (1982) points to two books in particular that reflected this perspective. *Silent Spring*, by Rachel Carson, and *Hard Tomatoes, Hard Times*, by Jim Hightower, argued that agricultural research concentrated on a narrow set of goals and did not adequately address consumer, environmental, and rural issues. This sentiment led to political pressure for a broader research agenda that would address the concerns of these groups. In 1990, language introduced into the farm bill established broad goals for agricultural research under the heading of "sustainability" (see box, "Technology and Sustainability").

Recommendations for change also came from within the scientific community. In 1972 and 1982, two reports by independent scientific committees (National Research Council, 1972, *The Pound Report*; Rockefeller Foundation, 1982, *The Winrock Report*) faulted the system for placing too much emphasis on applied research on local problems and not enough on basic biological research. Both reports recommended greater competition for research funds (instead of formula-based funding) and a shift away from applied research to more basic biological research. The underlying rationale for these recommendations was that the breakthroughs needed to maintain historical rates of productivity growth in agriculture would be based on advances in basic biological sciences. These reports argued that applied research would not generate the needed breakthroughs because it tended to focus on the commodities and production constraints important to specific localities and States. However, these reports did not receive unanimous approval in the scientific community. *The Pound Report* in particular was criticized for applying evaluation criteria better suited to the basic sciences than to the applied work conducted by the USDA-SAES system. Defenders of the system contended that the standards used to judge agricultural research should put greater emphasis on technological innovation and productivity-enhancing activities rather than on bench science (Ruttan, 1987). Schuh (1986) argued that a narrow focus on basic research would undermine the mission orientation of the land-grant university, which is "to bridge the gap between society's current problems and the frontiers of knowledge" (p. 7).

In 1981, the Office of Technology Assessment (OTA) released a report called *An Assessment of the United States Food and Agricultural Research System*. The OTA report praised the accomplishments of public agricultural research and called for increased support of the Federal-State system. However, it also pointed to many weaknesses in the system. The report cited a lack of well-defined goals for food and agricultural research and judged the process for research priority setting as inadequate. According to OTA, decisions about allocating research resources were made "ad hoc" and coordination between different components of the system was insufficient. The report also found inequity among the States about who paid for and benefited from agricultural research; food-surplus States often spent more on agricultural research than food-deficient States did, although the latter were major beneficiaries of lower food costs. The OTA study recommended that research should be concentrated in areas that would generate large social benefits but that the private sector would be unlikely to find profitable. Also, the report noted the need to maintain a balance between site-specific research and basic biological research. The OTA recommended a stronger USDA research program on issues in the national interest while keeping a portion of the system decentralized. This would allow the States to facilitate applied agricultural research on local or regional issues.

In 1989, the National Research Council (NRC) recommended a major increase in the use of competitive grants to allocate agricultural research funds. The NRC concluded that agricultural research as a whole was underfunded. Therefore, an increase in competitive grants should come from new resources rather than from a diversion of existing resources (National Research Council, 1989b). While funding for the USDA's competitive grants program was increased in the 1990 farm bill, this growth was largely at the expense of formula funding.

Changing Sources of Support for the SAES's

Two factors have strongly influenced State agricultural experiment station funding: (1) an outgrowth of these criticisms and recommendations and (2) the need to secure new sources of funding. As a result, the nature of financial support for the State agricultural experiment stations has changed significantly over the past several

Technology and Sustainability

Several concerns have focused public attention on sustainable agriculture, including environmental degradation, natural resource conservation, food safety, and the viability of family farms and rural communities. For example, some production practices currently employed by farmers contribute to the erosion of environmental quality and to the depletion of the natural resource base. Sustainable technologies, on the other hand, are designed to mitigate the effect of agricultural production on the natural resource base and on the environment. The decision to adopt alternatives to conventional production technologies hinges upon the relative profitability of these alternatives. Accordingly, the public debate about sustainability is centered around the trade-offs between economic, environmental, and social consequences of adopting alternative production technologies.

In the United States, pressure from interest groups seeking to improve the well-being of farmworkers, rural communities, and the environment have ultimately influenced legislation pertaining to technologies adopted by producers. In particular, the 1990 farm bill explicitly dealt with sustainability issues in several ways. First, a specific definition of sustainability was adopted. According to this congressional definition, sustainable agriculture is an:

> "...integrated system of plant and animal production practices having a site-specific application that will, over the long term a) satisfy human food and fiber needs; b) enhance environmental quality; c) efficiently use non-renewable resources and on-farm resources and integrate appropriate natural biological cycles and controls; d) sustain the economic viability of farm operations; e) enhance the quality of life for farmers and society as a whole" (PL-95-113, 91 Stat. 981, 7USC 3101, Sec. 1404).

Second, the farm bill directed USDA to ensure that competitive grants awarded under the National Research Initiative (NRI) were consistent with the development of sustainable agricultural systems. Finally, the farm bill encouraged research designed to increase the knowledge and application of sustainable production systems. In particular, the Secretary of Agriculture is directed to conduct research and extension projects that reduce chemical use on farms, improve low-input farm management practices, and help crop and livestock enterprises.

USDA's research agencies shoulder the principal responsibility of carrying out the farm bill mandate to steer agriculture in a sustainable direction. To do this task more effectively, USDA formed a panel to develop a protocol for sustainable agriculture. This protocol could be applied to each NRI project to evaluate its relevance for promoting more sustainable agriculture. In this fashion, the protocol could serve to provide a quantitative measure of the contribution of research to sustainability.

Difficulties persist with the application of this protocol to an evaluation of NRI grant applications. These difficulties are in part due to the controversy surrounding definitional issues in sustainable agriculture. The idea of sustainability is believed to be subject to widely varying interpretations. Many alternatives to the congressional definition are available. For example, Ruttan (1992 and 1994) identifies three broad approaches to defining sustainability. One definition stresses the long-term capacity to supply a growing population with agricultural commodities at a reasonable cost to consumers. A second definition views sustainability as an ecological issue because agricultural commodity production can disrupt the ecological balance of natural systems, cause pollution, and deplete the stock of nonrenewable resources. The third definition emphasizes not only natural resources and the environment but also rural communities. According to this view, guided by such traditional values as stewardship and self-reliance, rural communities can be revitalized by adopting a holistic approach to both the physical and cultural dimensions of agricultural production.

A second difficulty associated with carrying out the protocol is the potential trade-off between different goals of sustainability. A research project may enhance one goal of sustainability (for example, profitability) while compromising another (for example, environment). As an example, recent research comparing farming systems in east-central South Dakota by Dobbs, Smolnik, and Mends (1991) found that sustainable technologies, while providing obvious environmental benefits, are unlikely to be as profitable as conventional technologies.

Finally, there is also the issue of evaluating projects with the potential to affect sustainability. The sustainability protocol assigns a score of zero to projects that have no direct, presumably short-term, effect on sustainable systems. Most basic research would fall into this category, although they have the potential to contribute to sustainability. Therefore, some NRI managers believe that the current scoring system is biased toward accepting projects showing immediate potential effects on the environment and the natural resource base (National Research Council, 1994). By implication, projects having a potential to yield benefits over the long term will be overlooked.

Despite the difficulties in implementing sustainable agriculture, proponents of sustainability believe that U.S. agricultural research is too narrowly focused on increasing production efficiency. They argue that in order for this research to be relevant, greater accommodation must be made to address the needs of a broader constituency, a new research agenda should address not only the profitability but also the environmental and social implications of alternative technologies used in agriculture.

years. Between 1978 and 1994, the share of the research budget for these institutions that came from State governments fell from 55.1 percent to 47.4 percent, while total Federal support (USDA and other Federal agencies combined) rose slightly, from 30.7 percent to 33.0 percent (table 1). This reversed a long-term trend in which State support for the SAES's had been increasing at a faster rate than Federal support. While USDA contributions to the SAES system fell from 22.2 percent to 20.3 percent, increased support from other Federal agencies more than made up the difference. The nongovernmental share of funding (industry grants, product sales, and other sources, combined) had the most rapid rate of growth. This funding source increased from 14.3 percent to 19.7 percent of total research expenditures at these institutions. Research grants from industry grew from 5.1 percent to 7.2 percent during this period.

The recent decline in the relative contribution of State governments to public agricultural research is partly a result of the 1990-91 economic recession. It may also be due to the decline in agriculture's share in local economies, the falling number of farms, and the resulting decline in the political influence of farm lobbies. Empirical studies on the political economy of public agricultural research in the United States showed that States with large agricultural sectors often allocate a larger portion of their State budget to agricultural research (Peterson, 1969; Guttman, 1978; Huffman and Miranowski, 1981; Rose-Ackerman and Evenson, 1983). These studies also found that farmers who organized more effectively for collective action (for example, more concentrated farm structure or membership in farm cooperatives) could increase public agricultural research funding by State governments. Because of agriculture's falling share of the economy and the declining number of farms, these studies were pessimistic about the future support from States for agricultural research unless new political constituencies could be developed.

Table 1—Sources of funding for State agricultural experiment stations, 1978 and 1994

Source	1978		1994	
	$1,000	*Percent*	*$1,000*	*Percent*
Governmental:				
State governments	374,933	55.1	1,010,861	47.4
USDA	150,977	22.2	432,993	20.3
Other agencies	57,856	8.5	270,016	12.7
Nongovernmental:				
Industry grants	34,704	5.1	152,898	7.2
Product sales	40,061	5.9	116,704	5.5
Other	22,407	3.3	148,226	7.0
Total	680,938	100.0	2,131,698	100.0

Note: Percentages may not sum to 100 due to rounding.
Source: Economic Research Service compiled from U.S. Department of Agriculture, *Inventory of Agricultural Research*.

While new sources of funding allow the public research to expand into new areas, the trend toward increased reliance on support from the private sector has generated concerns. Specifically, public research programs could be disproportionately leveraged toward the needs of private industry rather than for the broader interests of farmers or consumers. For instance, a firm may give a grant to a university department if specified research is carried out. The university, in turn, may not charge the firm the full cost of doing the research because its buildings, equipment, and staff are considered a sunk cost. In a study of barley research in Canada, Ulrich, Furtan, and Schmitz (1986) found that when brewing and malting companies increased their financial support of public barley research, greater weight was given to improving malting quality rather than increasing yields. According to the study, higher yielding varieties would have been more beneficial to livestock producers. The study also concluded that while both the public and private sectors gained from the joint research effort, the social cost of private assistance was high. This is because increased attention to yield would have had higher social benefits.

According to USDA's *Inventory of Agricultural Research*, nearly 25 percent of private funds going to State agricultural research institutions were designated for animal production research in 1992. Increased concentration in the livestock industry facilitates direct financial support of university and experiment station research on animal production. Another area where joint public-private support of research is employed is for research on new industrial uses of agricultural commodities. Support from the private sector is not always oriented toward developing new or lower cost products. In 1992, nonprofit foundations funded over half the research conducted by State agricultural research institutions on the causes of rural poverty, for example (USDA, 1992).

Another major change in the financial support of the system occurred in the administration of Federal funds for State research institutions. A principal recommendation of the Pound, Winrock, OTA, and NRC reports was that a greater share of Federal funds for agricultural research should be allocated competitively instead of as formula funds. Formula funds are unrestricted block grants given to State research institutions. Competitive grants, on the other hand, are awarded to individual scientists or research teams based on peer-reviewed project proposals. Projects are for a fixed term of usually 1 to 5 years. The USDA initiated a competitive grant program in 1978 and expanded it in the 1990 farm bill with the National Research Initiative. During the past several years, scientists at SAES institutions also became more active in competing for research grants administered by other Federal agencies, such as the National Science Foundation (NSF) and the National Institutes of Health (NIH).

Since the 1960's, the share of Federal agricultural research dollars administered as formula funds has declined significantly (table 2). In 1970, formula funds were 61 percent of all Federal research funds going to SAES and cooperating institutions, and 87 percent of USDA-administered funds. By 1994, formula funding had fallen to 30 percent of Federal funds and 49 percent of USDA funds for agricultural research at these institutions. Not all of the decline in formula funds was the result of the increased use of competitive grants, however. Noncompetitive project grants also grew substantially. In 1965, USDA began a "special grants" program, which allocated funds noncompetitively to specific research institutions for projects earmarked by Congress. The SAES institutions also receive research grants directly from USDA in-house research agencies in the form of cooperative agreements (contract research). ARS, the Forest Service, and the Economic Research Service use cooperative agreements to fund specific studies in support of their research programs.

The choice of a funding mechanism has significant implications on the character of agricultural research conducted in the State research system (see box, "Institutional versus Project Support of Agricultural Research"). Formula funding often encourages recipient institutions to undertake major mission-oriented applied research and technology development programs (Ruttan, 1982). It also relieves scientists from the burden of grant seeking, making more time available for research activities (Huffman and Just, 1994). Project support, on the other hand, encourages the research institute to become more responsive to the priorities established by the funding agency. It also enables USDA to draw upon the research capacity outside the land-grant university system (National Research Council, 1989b). According to a study by Frisvold and Day (1993), a larger share of competitive grants is allocated toward research on basic biology and animal production compared with other types of USDA funding mechanisms.[4] These are areas that are likely to generate new knowledge and technologies that can be applied nationally or regionally. Formula funds,

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[4] This is partly due to the characteristics of competitive grant programs generally and partly due to how the NRI is designed. Congress mandated that NRI funds be allocated among six areas in the following proportions: plant systems (40 percent), animal systems (25 percent), natural resources (20 percent), nutrition (7 percent), processing (4 percent), and markets, trade, and rural development (4 percent).

Table 2—Federal support for State agricultural experiment stations

			Project support										
Year	USDA formula funds		USDA competitive grants		USDA special grants		USDA contracts and other[1]		Other Federal[2]		Total project support[3]		Total Federal support
	$1,000	*Pct.*	*$1,000*	*Pct.*	*$1,000*	*Pct.*	*$1,000*	*Pct.*	*$1,000*	*Pct.*	*$1,000*	*Pct.*	*$1,000*
1970	55,572	61	0	0	1,581	2	6,974	8	27,308	30	35,863	39	91,435
1975	80,948	58	0	0	10,448	8	11,686	8	35,300	26	57,434	42	138,382
1980	121,124	46	9,480	4	9,627	4	50,040	19	71,581	32	140,728	54	261,852
1985	188,232	51	11,514	3	20,395	6	36,847	10	112,414	31	181,170	49	369,402
1990	191,711	37	31,173	6	47,605	9	55,133	11	188,606	37	322,517	63	514,228
1992	209,400	35	40,057	7	61,914	10	65,981	11	221,315	37	389,267	65	598,667
1994	214,254	30	62,542	9	69,162	10	87,035	12	270,016	38	488,755	70	703,009
Gini[4]	0.34		0.63		0.59		0.55						
					0.51								

[1] Includes other research grants administered by CSREES (formally CSRS). [2] Including National Institutes of Health, National Science Foundation, U.S. Agency for International Development, Department of Defense, Department of Energy, National Aeronautics and Space Administration, Tennessee Valley Authority, Department of Health and Human Services, and other non-USDA agencies. This includes a mix of competitive and noncompetitive project grants. [3] May not add due to rounding. [4] Gini coefficients show the distribution of USDA funding among States (based on 1992 budget allocation).

Source: Economic Research Service compiled from U.S. Department of Agriculture, *Inventory of Agricultural Research*.

Institutional versus Project Support of Agricultural Research

The Federal Government supports both institutional and project funding of agricultural research. Historically, institutional support as unrestricted block grants to research institutions has been the primary form of Federal support for agricultural research. How these funds are used is left to the discretion of the receiving institutions. Project support for research, on the other hand, provides funds to individual researchers or teams for research on specific topics. Projects are for a fixed term of usually 1-5 years. Project funding by the USDA was initiated in 1965 with the Special Grants program and expanded in 1977 with the Competitive Grants Program.

Institutional support of research encourages research institutions to undertake major mission-oriented applied research programs. It also relieves researchers from the burden of grant seeking, freeing up more time for research activities. Project support, on the other hand, can encourage more fundamental, cutting-edge research and quickly focus research resources on newly emerging issues. Project funding also enables the USDA to draw upon research resources outside the land-grant system. Both systems of research support have merits, and the appropriate question for science policy is not whether one system of support is better than another, but what is the appropriate mix of the two systems for optimal research performance?

Federal Institutional Support for Agricultural Research

Formula funds. These are unrestricted block grants allocated to State agricultural experiment stations (SAES's) and cooperating institutions for research on agriculture, forestry, and veterinary medicine. Funds are allocated to States based on congressionally mandated formulas and administered by USDA's Cooperative State Research, Education, and Extension Service (CREES) in the following manner:

1. *Hatch Act of 1887*—supports agricultural research at SAES's;
2. *Evans-Allen Program* (Section 1455 of 1977 Farm Bill)—supports agricultural research at 1890 Colleges and Tuskegee University;
3. *McIntire-Stennis Act of 1962*—supports forestry research at the Forestry Colleges and SAES's;
4. *Animal Health and Disease Research Program* (Section 1433 of 1977 Farm Bill)—supports veterinary research at veterinary schools and SAES's.

Intramural research. Institutional support is also provided for research conducted at USDA research-performing agencies. These are primarily the Agricultural Research Service, Forest Service, and Economic Research Service.

Federal Project Support of Agricultural Research

The USDA and other Federal agencies also provide funds for specific projects of fixed terms.

USDA Competitive Grants. These grants are awarded on the basis of submitted research proposals that are peer-reviewed. Research proposals are considered for six broad categories: (1) natural resources and the environment; (2) nutrition, food quality, and health; (3) animal systems; (4) plant systems; (5) markets and trade; and (6) policy. Funds for the Competitive Grant Program were authorized by the National Research Initiative of the 1990 Farm Bill and are administered by CSREES.

USDA Special Grants. These grants are congressionally earmarked funds to specific universities or entities for specific research projects. Special Grants were first authorized in 1965 by P.L. 89-106, and are administered by CSREES.

Other USDA contracts, grants, and cooperative agreements. project support to SAES's from USDA research-performing agencies (Agricultural Research Service, Economic Research Service, and Forest Service).

Non-USDA federal grants for agricultural research. Several non-USDA Federal Agencies support agricultural research projects at State universities and research entities. These include the Department of Energy, Department of Defense, Department of Health and Human Services, National Institutes of Health, National Science Foundation, Tennessee Valley Authority, National Air and Space Agency, and the Agency for International Development.

special grants, and contract research, on the other hand, were more likely to support research for natural resource management, rural development, and for improving community services and the environment. Information and technology to address these issues are often more location-specific (Frisvold and Day, 1993).

Changes in funding mechanisms also affect the distribution of Federal funds among States. Competitive grants may favor States with strong basic sciences research at the expense of universities that emphasize applied technology development. Many States rely almost exclusively on formula funds for Federal support of agricultural research. Formula funds account for more than 70 percent of USDA research funds going to SAES's in 14 States and for more than 85 percent of funds in 5 States. California, on the other hand, receives most of its USDA research funds from a combination of competitive grants and contracts. Hawaii, North Dakota, and Massachusetts receive more than 40 percent of their USDA funds as special grants (Frisvold and Day, 1993). Buttel (1986) hypothesized that increased reliance on competitive grants might create a two-tier system of "haves" and "have-nots" within the land-grant university system. Frisvold and Day (1993) found that universities with highly ranked programs in basic biological sciences fared better than others in obtaining USDA competitive grants. They also found that formula funds were more equally distributed among States than project grants, as indicated by the smaller Gini coefficient associated with formula funds in table 2 (a Gini coefficient of zero would mean that each State receives an equal share of USDA research funds, while a value of 1.0 would mean that one State receives all research funds). Formula funds were more evenly distributed among States than project grants. This is especially true for the allocation of competitive grants and special grants, although these alternative funding mechanisms often offset each other. While the Gini coefficients for competitive grants and special grants are 0.63 and 0.59, respectively, the Gini coefficient for all project support is only 0.51 (table 2). In other words, a larger share of special grants went to States that received a smaller share of competitive grants. This tendency served to mitigate the distributional implications of increasing competitive funding.

Research Priorities for Public Agricultural Research

The increased reliance on project-oriented support for agricultural research in the Federal-State system places a greater burden for research management on the funding agencies. It shifts responsibility for priority setting from the experiment station to the funding agency. It also makes coordination between science-oriented research and technology-oriented research more problematic. Project-oriented research is less likely to be integrated into the programmatic themes established by an experiment station.

The growth in agricultural research conducted by the private sector also has important implications for public agricultural research. Research administrators in the public sector must increasingly justify their comparative advantage in conducting applied research compared with the private sector.

The USDA's Current Research Information System (CRIS) provides data about funding allocations for agricultural research in the Federal-State system. This system employs a four-way classification of agricultural research expenditures by commodity or resource, by field of science, by research problem area, and by activity. Each agricultural research project is assigned at least one classification code in each of these four areas. An annual USDA publication, the *Inventory of Agricultural Research*, gives the allocation of research expenditures and scientist-years by these classifications for Federal and State agricultural research institutions.

Allocation of Research Resources Between Programs and Goals

In 1992, more than $2.9 billion were spent on public agricultural research (table 3). Crop, livestock, and forestry research made up just more than 71 percent of total spending. Nearly 12 percent went for research on natural resource conservation and management, principally research on soil, water, and wildlife resources. The remaining 17 percent was distributed among four other program areas, including food science, general resources and technology, competition and trade, and research on rural people, communities and institutions.

Another indication of the goals of this research is given in figure 5. This figure shows the allocation of public research expenditures for each of the nine major research problem areas defined in CRIS for 1973, 1982, and 1992, in constant 1992 dollars. The share of research expenditures for these goals has remained stable during the past 20 years, with some minor changes. More than 70 percent of public agricultural research expenditures went to three goals: (1) reduction of production costs of food and forest products; (2) protection of forests, crops, and livestock from pests and diseases; and (3) conservation and management of natural resources. Research to protect agricultural products from pests and diseases increased in real terms and currently accounts for nearly a fourth of total agricultural research spending.

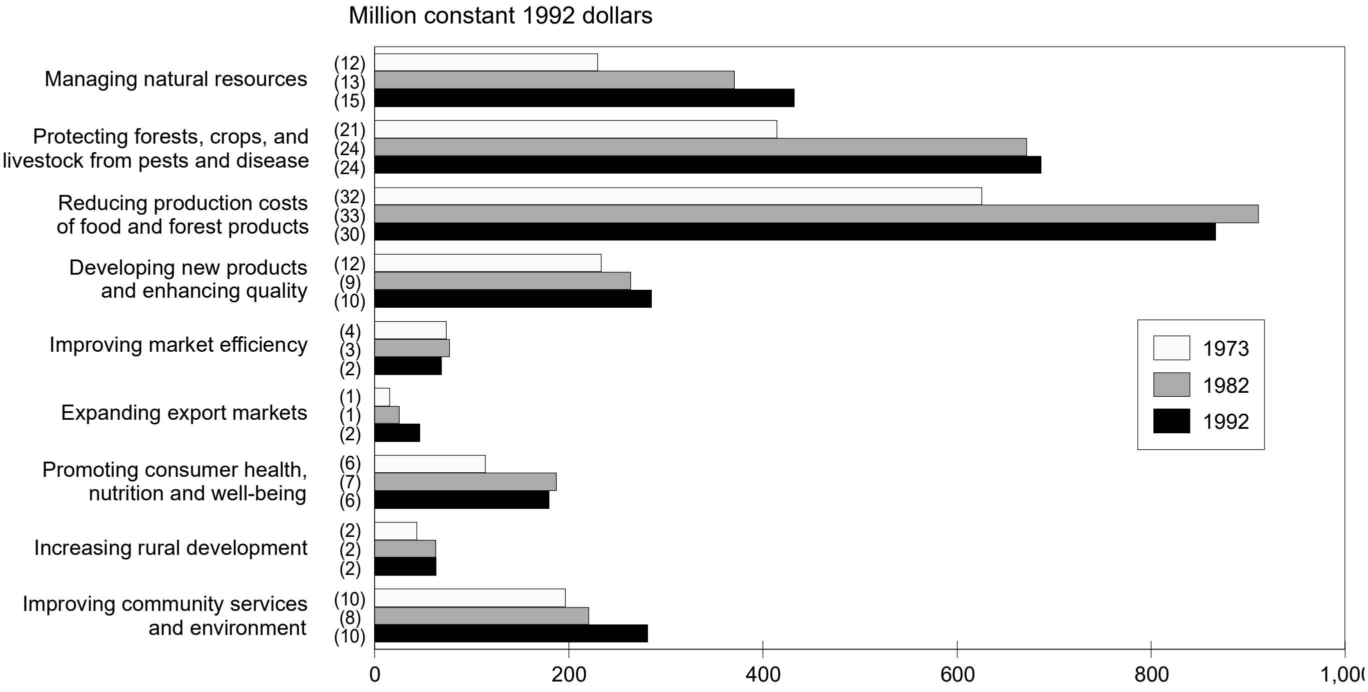
Table 3—Public research expenditures by program area, 1992

Research program area	Expenditure	Share of total
	$1,000	*Percent*
Crops	999,690	34.4
Animals	691,041	23.8
Forest resources	381,965	13.1
Natural resources	335,418	11.5
Food science and nutrition	169,302	5.8
Competition, trade, and adjustment	139,726	4.8
General resource and technology	100,310	3.5
People, communities and institutions	88,353	3.0
Unclassified	7,356	0.1
Total	2,913,161	100.0

Source: Economic Research Service compiled from U.S. Department of Agriculture, *Inventory of Agricultural Research.*

Figure 5

Allocation of USDA-SAES research expenditures, by goal[1]



Note: Percentage of annual total expenditures in parentheses. Totals may not sum due to rounding.

[1] Annual expenditures adjusted for inflation by cost-of-research deflator.

Source: Economic Research Service. Data derived from Alston and Pardey, 1995.

Research for natural resource management also experienced steady growth in real terms since 1973. Its share of the total budget increased from 12 percent in 1973 to 15 percent in 1992. On the other hand, research expenditures to reduce production costs declined in real terms between 1982 and 1992, falling from 33 percent to 30 percent of the total by 1992. The remaining 30 percent of research expenditures is allocated among the six remaining goals, which include post-harvest use, consumer and rural issues, and international development.[5]

Economic Analysis of Research Resource Allocation[6]

The budget allocations of the public agricultural research shown in table 3 and figure 5 do not indicate whether too much or too little research is being allocated to any particular program area or goal. Measuring the allocative efficiency of these budget allocations requires expert opinion and analysis of technological possibilities and the potential economic and social impacts of new technology. Ruttan (1982) characterized the setting of agricultural research priorities as bringing information to bear on two principal questions:

> (1) What are the possibilities of advancing knowledge or technology if resources are allocated to a particular commodity, problem, or discipline? and
>
> (2) What will be the value to society of the new knowledge or the new technology if the research effort is successful?

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[5] Other ways of broadly categorizing agricultural research expenditures have also been developed. The Joint Council for Food and Agricultural Sciences (JCFAS), which advises the USDA on research priorities, developed seven overall categories for allocating research expenditures. The Experiment Station Committee on Policy (ESCOP) uses a slightly different seven-category system and conducts an annual budget review and priority-setting exercise for the SAES's. These two systems correspond closely to the eight research program areas shown in table 3.

[6] Alston, Norton, and Pardey (1995) present a comprehensive review of analytical models for allocating public resources for agricultural research. See also Ruttan (1982, pp. 262-97) and Fox (1987).

Scientists who are on the leading edge of a research discipline or problem being considered are probably best able to make judgments about the first question. The answer to the second question often requires information from economic or social sciences. Answers to these questions help identify what research should be given highest priority. Yet, they do not shed much light on whether the public or private sector should bear the primary responsibility for conducting this research. Increasingly, public agricultural research administrators need to pose a third question to their research allocation decisions:

> (3) Of the research required to sustain productivity growth and meet other goals, what research will not be undertaken by the private sector?

The private sector will not conduct some kinds of research, while in other areas, the private sector is likely to underinvest. The rationale for public support of research is clearest for socially valuable research that the private sector does not find profitable to fund (see box, "Research on Public Goods"). Institutional linkages between public and private research can help assure that research efforts are not redundant and that new scientific knowledge is put to commercial use quickly (see "Public-Private Collaboration in Agricultural Research," p. 51, for a discussion of this issue).

Formal, analytical tools can help policymakers in allocating increasingly scarce research resources. These tools also serve to make public programs more accountable. At the same time, it is possible to overmanage a research system. Success in research is difficult to predict and innovation requires flexibility in order that scientific ingenuity is not stifled. Economic input into research planning and evaluation may be best conducted at the program level (that is, by commodities, disciplines,

Research on Public Goods

Several important areas of public concern have little commercial benefit to private researchers. Therefore, the public sector must conduct research to reach the level wanted by society as a whole.

Natural Resources and Environmental Research

Natural resources research covers the use, management, and conservation of natural resources and the environment. Natural resources research funded by USDA research agencies fell between 1978 and 1992, to $267 million. USDA in-house research in natural resources can be separated into six different topics: soil, land assessment and management, water, forest products, pollution, and other research (including interdisciplinary). Forest products research received the most funds in both 1978 and 1992. Soil research funding grew slightly over this period. The most dramatic increase was in the category "Other," specifically in interdisciplinary research, weather research, and remote sensing. Funds for water, land assessment, pollution, and forest products declined between 1978 and 1992.

Institutions outside the USDA are now conducting an increasing percentage of the natural resources and environmental research funded by the agency. Natural resource funding at SAES and cooperative institutions is spread relatively evenly among the different research topics. The category "Other" is the largest recipient of funds (with the leading research areas being "Interdisciplinary Research" and "Fish and Other Wildlife"). Forest Products received the next highest level of appropriations. Unlike USDA in-house research, the funding of each SAES research topic increased from 1978 to 1992 (to $465 million). State tax revenues were an increasingly important funding source for natural resources research at SAES.

Research on Food Safety, Nutrition, and Other Consumer Needs

One of the nine major goals of the public agricultural research system is to "protect consumer health and improve the nutrition and well-being of the American people" (CRIS, 1993). Research areas likely to be underfunded without public efforts are general nutrition research, research on contaminants, and various health hazards.

Most of USDA's in-house research focused on, in order of funding received in 1992, human nutrition, microbial contamination, and toxic contaminants. Research on human nutrition, microbial contaminants and natural toxins increased between 1978 and 1992. However, USDA research on consumer issues as a whole fell approximately 14 percent between 1978 and 1992 to less than $34 million (in real terms). Generally, USDA moved away from the broader areas of food-related research to focus on high-profile research with a larger public good component.

At SAES and other institutions, the priority patterns were similar to those at USDA, with nutrition, microbial, and toxic contaminant research receiving the most funding. However, funding for food-related research increased and the distribution of research funds was broader across other categories.

USDA appears to have reduced its role in consumer research overall, except microbial and human nutrition research. SAES and other institutions continued to play an increasing part in food and related research.

and broadly defined research problems) rather than by individual projects. Applying formal models of research allocation is also more difficult for non-commodity research, such as more basic research that cuts across several commodities and applied research that generates nonmarket benefits.

Benefit-cost analysis, or the "economic surplus" approach. Benefit-cost analysis compares the present value of the estimated research costs of a project or program to its anticipated benefits. It requires estimates of expected yield increases over time under various levels of research, expected adoption rates, and anticipated aggregate production and price effects. The advantage of this method is that a consistent measure of economic efficiency is applied to each alternative. In the last several years, significant progress has been made in laying the analytical foundation for doing cost/benefit analysis of research resource allocation (Alston, Norton, and Pardey, 1995).

There is a practical barrier to estimating detailed prospective rates of return. Scientists often have difficulty providing informed mean estimates of the effects of research on yield or productivity increases where the scientific outcome of the research is yet unknown. Doing this for basic research would be particularly difficult where the connection of the research to a specific future commercial application is less clear. Past attempts to estimate the broader effects of new technologies suggest the potential difficulties with this approach. For example, in retrospect, scientists appeared to have grossly overestimated the yield effects of bovine somatotropin (McClelland, Kuchler, and Reilly, 1991). After the product was near release, enough information was finally available to estimate yield changes. In fact, onfarm improvement in milk production efficiency is likely be less than 10 percent compared with early estimates of 30 percent or more. On the other hand, scientists may underestimate the effect of scientific and technological advances in other disciplines on their own research. This may lead them to understate the potential for technological breakthroughs. For example, plant breeders may be unable to assess the possibility of advances in plant genetics, although these advances are likely to significantly affect the productivity of their own research.

Estimates of the rate of return to research as a guide to funding. An approach that avoids the problem of eliciting prospective evaluations of proposed research projects is to base current research allocation on estimated rates of return to past research. Rate of return estimates can provide insights into the amount of resources that should be allocated to research, how these resources should be allocated among program areas, and who should fund different kinds of research (see "Economic Returns to Public Agricultural Research," p. 24, and the Appendix for detailed discussions of this issue). The approach seems to suggest very broad resource allocation (for example, basic versus applied research and livestock versus crop research). However, at a more disaggregated level there is a large degree of variability and uncertainty in these estimates.

Congruence models. A simple but somewhat naive approach for evaluating the allocation of research expenditures is the congruence model (also called the parity model). The congruence model compares research expenditures with the economic importance of a particular commodity, resource, production stage, or region. It is most often employed by comparing research expenditures among agricultural commodities. Congruence implies that each commodity receives the same level of research funding as a percentage of either the commodity's gross value of production or value-added. The parity idea is based on two assumptions: that the possibilities for technological advance for a given level of research are the same for all commodities; and that the value of a scientific or technical innovation is proportional to the value of the commodity. While both assumptions are simplistic, the congruence model represents a useful starting point for assessing the allocation of research resource. It is a straightforward way to use economic data to put research expenditures into perspective. According to Ruttan (1982), departures from parity should be based on explicit rationale. Such rationales might be the extent to which the private sector can support research in a commodity, judgments about differences in technological opportunities, and objectives other than economic efficiency.

In 1989, an average of $13.00 was spent on research for each $1,000 of production (congruence ratio) of 12 selected commodities: vegetables, corn, fruits, soybean, forage, wheat, cotton, sorghum, sugar, other grains, rice, and peanuts (fig. 6). Private seed companies conducted a large share of research for corn, sorghum, sugar, and vegetables.[7] If only public expenditures are taken into account, the congruence ratio for corn is far lower than for the other 11 commodities. Once private expenditures are added, however, corn research is much closer to the average congruence ratio. On the other hand, congru-

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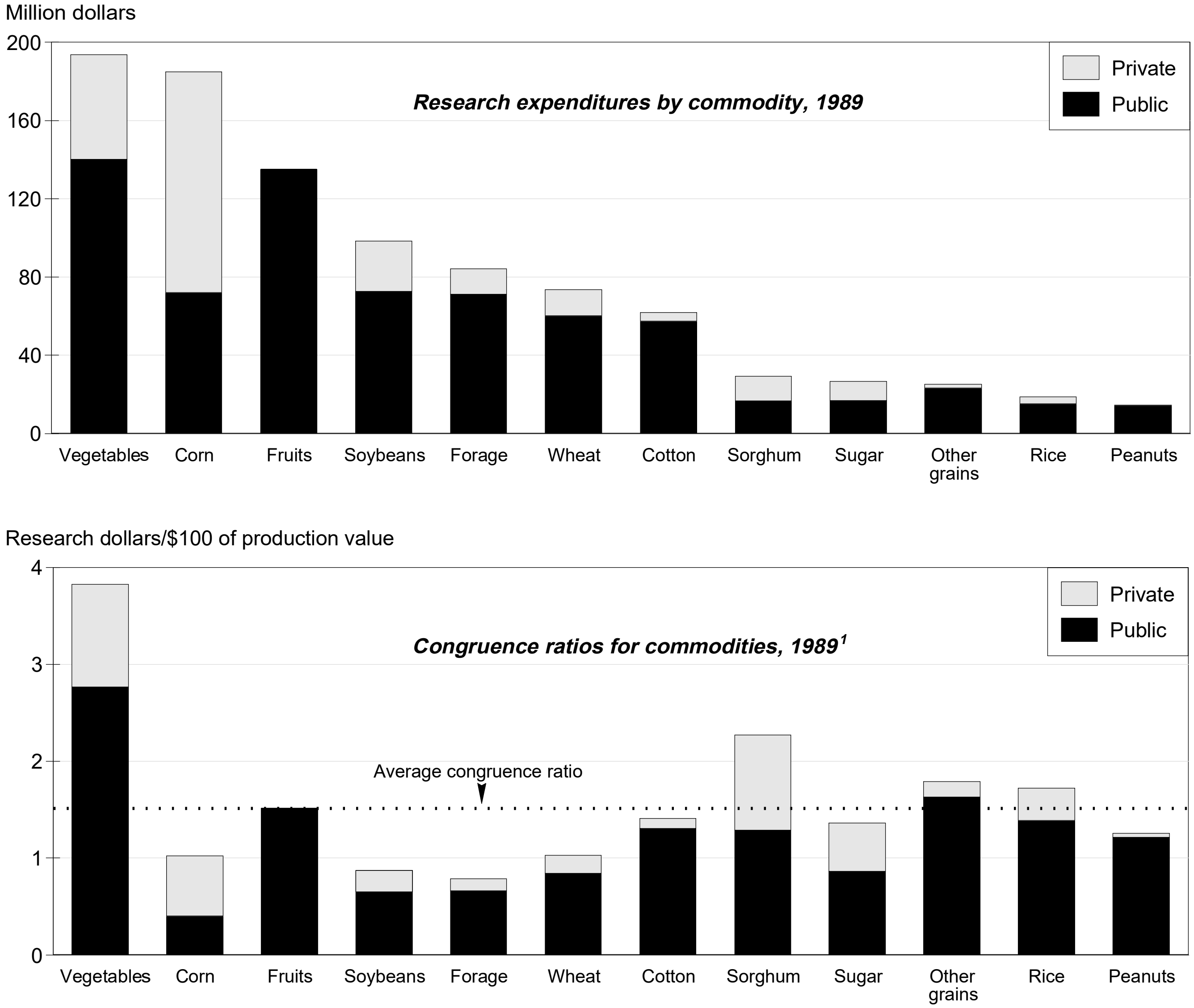
[7] The estimates for private plant-breeding expenditures are derived from a survey conducted by Kalton, Richardson, and Frey (1989). See table 17 for more detailed information from this survey. While the estimates for private research include only plant breeding, this is one field of science where public and private research are likely to overlap. Around 70 to 80 percent of public research on crop commodities is for increasing biological efficiency and crop protection (Huffman and Evenson, 1993).

Figure 6

Congruence of commodity research



[1] Congruence ratios are one way of comparing research spending among commodities. The congruence ratio is the amount spent on research as a percentage of the value of production for a commodity. For example, of the commodities shown in this figure, research spending equals 1.5 percent of the value of production on average (average congruence ratio). For vegetables, research spending is almost 4 percent of production value. For corn, soybeans, forage, and wheat, research spending is at or below 1 percent of production value.

Sources: Economic Research Service. Data for public research expenditures derived from USDA, *Inventory of Agricultural Research* private plant breeding data derived from Kalton, Richardson, and Frey (1989).

ence ratios for sorghum, and to a lesser extent, rice, exceed the average once the level of private research for these crops is included.

The congruence model is limited as an allocation tool since it fails to include the timing of research benefits and costs, discount rates, probable adoption patterns, technological opportunities, and market characteristics of different commodities. Nor does it take into account possible economies of scale or diminishing returns in research. There is a minimum size needed for a commodity research program to be viable. This may explain why the congruence ratios for groups of commodities, like vegetables and fruits, are higher than those for single commodities. Each fruit and vegetable crop will need a research program, which must meet a certain minimum size to be effective. Also, once a certain level of funding is reached, the potential value of additional research (that is, opportunities at the margin) may be diminished. For example, while the congruence ratios for corn and soybeans are below average, gross research funding for these crops is quite large.

Scoring models. Agricultural policy is concerned not only with enhancing production efficiency but also with equity, environmental protection, and the quality of rural life. Scoring models attempt to take into account a broader set of objectives for agricultural research. A research agency or governing committee first develops a set of criteria for measuring research objectives and gives each criterion a weight according to its relative importance. A panel of reviewers then scores each proposed project or program based on each criterion. These scores provide a ranking for the set of possible research resource allocations. The drawbacks of the scoring approach include the following: the expense of participation in the review panel, ranking subjectivity (real or perceived), and the lack of measures to weed out redundancy. Outcomes are determined by how much weight is given to each goal. When used in isolation from other methods, scoring exercises have generally been unsatisfactory. In practice, scoring has been more useful when combined with benefit/cost analysis. For example, if both equity and efficiency are stated as goals for research, then the use of benefit/cost analysis can determine how much economic efficiency might have to be given up to attain a desired distribution of research benefits.

Policy Implications

The rate of growth in public funding for agricultural research has significantly slowed since the mid-1970's. Furthermore, considerable resources are devoted to simply maintaining current productivity levels. These factors constrain the ability of the public agricultural research system to respond to a broadening set of societal demands concerning agricultural and food technology. State institutions are relying more heavily on the private sector for new sources of funding. Private contributions could exert a disproportionate influence on the research agenda of public institutions.

Federal support for agricultural research at land-grant universities and SAES's is undergoing significant institutional change. Federal funds have moved away from the traditional block grant (formula-funding) system to project-based support. Formula funds account for less than a third of all Federal funds for agricultural research at State institutions, and about a half of the extramural research funds administered by the USDA. Project-based support may be in the form of competitive or noncompetitive grants. Competitive grants are often allocated less equally among States than are formula funds, with a larger share going to universities with the strongest basic research programs in biological sciences. However, the allocation of noncompetitive, congressionally earmarked grants generally counterbalances the distribution of competitive grants. Increased reliance on project-based funding may reduce a research institute's ability to undertake major mission-oriented applied research. It also diverts scientific resources away from research to grant-seeking activities. On the other hand, the use of competitive research grants enables the Federal Government to draw upon research resources outside the land-grant university system. This may encourage more fundamental, cutting-edge research for agriculture.

Increasingly scarce resources for public agricultural research place a greater burden on research administrators to allocate research resources to high-priority areas. They must carefully assess public versus private—and Federal versus State—responsibilities in science and technology development. Economic cost-benefit analysis can be a useful tool for identifying high-payoff areas, although assessing non-market benefits from research is more problematic.

Economic Returns to Public Agricultural Research

A frequently used measure of research effectiveness is the rate of return earned by research investments. Many studies of the social rate of return to public agricultural research have been conducted. These studies have assessed both aggregate investments in agricultural research and various components of the agricultural system, considered different periods, and used different methodological approaches. These studies have, for the most part, found high social rates of return for most categories of agricultural research.

Conceptual Foundation for Measuring the Social Rate of Return to Research

The conceptual basis for the social rate of return to aggregate public research is drawn from straightforward estimation of the internal rate of return to an investment by a firm or household. Facing an investment decision at time *t*, the firm or household could estimate the flow of benefits (net of operating costs and depreciation) it received from the investment over time (B_{t+I}, for $I = 1,...,L$ where L is the life of the investment) against the initial cost of the investment (C_t). The internal rate of return of the investment is the value of r which solves the equation:

$$C_t = \frac{B_{t+1}}{(1+r)} + \frac{B_{t+2}}{(1+r)^2} + \ldots + \frac{B_{t+L}}{(1+r)^L} \qquad (1)$$

For the special case where the flow of benefits is constant over time and continues indefinitely, equation 1 can be analytically solved for r:

$$r = \frac{B}{C_t} \qquad (2)$$

In this simple example, if a dollar invested generated an annual net flow of returns of 50 cents, the rate of return would be 50 percent. More realistic cases where returns vary over time and where the life of the investment are limited require numerical solution of equation 1.

There are many complexities in measuring the rate of return even for a standard investment by a private firm and these complexities can pose even greater problems for estimating the social rate of return to research (see box "Social versus Private Returns to Research"). The biggest difference between measuring the private rate of return to a firm and the social rate of return is that, conceptually, the social return to an investment includes not only the returns to the technology developer but also to farmers, other producers, consumers, and other members of society. The social return to a private research investment is usually higher than the private return to the firm. Inventors frequently cannot appropriate all the benefits of their inventions because "spillover" benefits accrue to other users or consumers. Empirical studies validate the finding that the social rate of return to private research exceeds the private return.[8] This finding supports the hypothesis that the private market economy underinvests in research. Because the Federal Government is concerned with all members of society, economists argue that public decisions should use the social rate of return as a guide to determine whether research funding is adequate.

The distribution of research gains among consumers, producers, and other segments of society is also important in public decisions. A high rate of return generally means, however, that the gains to winners from the new technology exceed the losses to those who may lose from the new technology. In principle then, the gainers could compensate the losers so that everyone in the economy would be better off. Whether and how such compensation occurs is up to the political system. Also, it depends, in part, on whether people have equal opportunity to take advantage of new technological opportunities.

Federally funded research organizations generally do not privately capture the returns to publicly funded research and were legally barred from doing so until 1980.[9] This feature of public research means there is not a conceptually comparable private return to public research. The beneficiaries of public agricultural research are those who use the knowledge generated in their production processes and in their decisions. These beneficiaries may be manufacturing firms that produce and sell improved inputs to farmers or that manufacture food and fiber products for consumers. New knowledge generated from research may also be used directly by farmers in their production decisions, by consumers in their consumption decisions, and by government agencies in public policy decisions. Generally, the benefits of research extend beyond the initial users. Benefits spread to other parts of the economy when the new technology results in lower production costs for farmers and, eventually, lower product prices for consumers. In this way, the benefits of, for example, a new seed variety partly accrue to the firm that produces the seed but also flow to farmers, purchasers of the farm product, and consumers.

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[8] For example, Mansfield and others (1977) estimated that the social rates of returns for manufacturing innovations were clustered around 50 percent while the private rates were around 25 percent.

[9] In fact, the economic benefits to research are highest when new technologies are priced only to cover the input cost of producing them and do not include monopoly "rents" to compensate for the inventive effort embodied in the technology.

Social versus Private Returns to Research: Issues of Measurement

The direct economic benefits of research are measured by examining how the improved technology reduces the cost of output. Reductions in the cost of output generally result in some combination of higher returns to producers, lower prices, and more consumption. Some complications that arise in estimating the social rate of return are unique to the assessment of public investment in research. Measurement issues include:

✦ ***The private rate of return does not include spillover benefits (or costs).*** In principle, the social return to a research investment includes any returns to the innovator plus returns to farmers, other producers, consumers, and other members of society. Because of spillovers, the social return to private research is usually much higher than the private firm's return.

✦ ***Some spillovers are not included in estimated social rates of return.*** Rate-of-return estimates have generally not included research benefits that spill into the United States (from other countries) or out from the United States (to other countries). Therefore, benefits of federally funded research that do not accrue to U.S. citizens are treated separately. Spillovers into and out of non-agricultural sectors also generally are not included. Failure to include these spillovers can lead to biased estimates. Failure to attribute gains to private research funding can lead to an overestimation of the returns to public research.

✦ ***Global spillovers are significant.***

✦ ***The depreciation cost associated with the stock of technical knowledge is difficult to estimate.*** Some analysts assume that knowledge does not depreciate. If research stopped and no new knowledge was uncovered, technological progress would stop but would not regress. At least for some forms of more applied agricultural technology, this assumption is not accurate; pests develop resistance to new pesticides over time and thus the value of research on pesticides depreciates over time. Without a steady stream of new research, agricultural productivity would fall rather than simply stop growing.

✦ ***Benefits from research can be realized only several years after the research is conducted.*** There are several sources of lags: (1) A particular R&D project may take several years to complete, and application of basic research results may require further applied research and development; (2) time between development and commercial production may be several years, particularly if commercialization requires Federal approval of the safety and efficacy of the technology; (3) full commercial adoption generally occurs only after a period of several years; (4) use of a technology will cease completely when a superior technology appears.

✦ ***Market prices may not be the correct measure for assessing social returns.*** Valuation of some effects of new technology, such as effects on natural resources and the environment, health, communities and families, and rural landscape, is difficult because market prices do not exist.

The methodologies generally used to estimate the social rate of return to agricultural research focus on observed changes in market behavior and market prices. Statistical approaches that analyze the production efficiency of the economy cannot capture some effects of a technology on producers and consumers. In particular, rate-of-return studies do not measure the benefits of improved consumer and governmental decisionmaking and only capture some environmental benefits or costs of new technology (see box, "Social Benefits Not Captured in Rate of Return Estimates").

New technologies may not be beneficial to all parts of the economy and society. Negative effects of the technology on the environment, natural resources, health, or community and family life may lead private firms to estimate a return to research that exceeds the social return if the offending activities are not taxed or regulated. Based on this private profit incentive, the market economy may overinvest in some types of research. Researchers currently lack the empirical basis for estimating the full social rate of return to research that accounts for all the societal effects of new technologies.

The Social Rate of Return as a Guide to Funding Decisions

Statistical estimates of historical rates of return to agricultural research can yield insights on how much resources should be allocated to research, how those resources should be allocated among research programs, and who should assume primary responsibility for funding different types of research. An important consideration in using rates of return to research in policy analysis is that they reflect returns to past research. Ideally, current research decisions should be based on the evaluation of the rate of return to projects currently being considered for funding. While eliciting unbiased evaluations is difficult, cost-benefit approaches have been developed for this purpose.

Social Benefits Not Captured in Rate-of-Return Estimates

Traditional methods for estimating returns to agricultural research were designed primarily to consider improvements in the productive efficiency of the agricultural economy. Effects of research where benefits are not well captured in traditional rate-of-return studies include:

✦ ***Consumer decisionmaking, family life, and community development***. Research to understand nutrition and health effects of food consumption choices is effective if it leads consumers to make food choices that help them to be healthier and to live longer. There are benefits to the economy of a healthier population, such as improved productivity while on the job or in school, reduced medical expenditures, and fewer absences from work or school. In principle, these changes could be measured. Improvements in family life and community development are less easily defined and even more difficult to value. Other evidence of effectiveness of research on these issues may provide better guidance on the adequacy and allocation of funding.

✦ ***Public decisionmaking***. Firmer scientific or social scientific understanding can identify problems requiring government intervention, can explain that a perceived problem is less severe than generally believed, and can be necessary to estimate the effectiveness and cost of proposed remedies. For example, research efforts directed toward understanding changes in surface and groundwater quality, food safety, global climate change, and changes in air quality are aimed at helping public decisionmakers decide what to do about these problems. Estimating benefits requires that the social outcome resulting from the actual decision be contrasted with the counterfactual outcome resulting from decisions that would have been made with mostly scientific information.

✦ ***Environmental technologies***. For regulated or taxed environmental consequences, traditional rate-of-return studies will capture the environmental benefits of new technology. These benefits are known because the new technology reduces the cost of compliance with the regulation or the amount of environmental tax. This reduced cost reflects increased productive efficiency. For environmental problems that are not regulated or where the regulation or tax is insufficient to reduce pollution to a socially desirable level, traditional rate-of-return studies will undervalue research on new technologies that reduce pollution.

A simple investment rule in the rate-of-return literature says that a firm should invest in a project if the rate of return exceeds the interest rate the firm must pay on borrowed funds. Modern finance theory has revealed many reasons, such as risk, why this simple rule may not apply even for the firm undertaking a standard investment. A number of additional issues arise in assessing public investments, especially for research (see box, “Using the Rate of Return to Make Research Funding Decisions”). The rate below which projects are not funded is sometimes called the hurdle rate. There is considerable disagreement concerning the appropriate hurdle rate for public investments. Based on estimates of the social discount rate or on the risk-free market rate of interest, a hurdle rate of 5 percent or less could be justified for public investments. However, the economic efficiency for agricultural research cannot be judged apart from the return to investments in other areas of the economy. While additional funds to agricultural research may yield net benefits, this would not be the most efficient use of funds if other areas of the economy were more seriously underfunded. Fox (1985) argues that the social rate of return to agricultural research should be compared with the social rather than the private rate of return to public and private investments. Using data from *Forbes* (Jan. 14, 1985) on 5-year average rates of return for 1,000 U.S. firms, Fox estimated that the social rate of return to assets ranged from 17.8 percent to 22.8 percent per year. Ruttan (1980) argued that a level of investment in agricultural research that would push rates of return to below 20 percent would be in the public interest.

Comparing the estimated rate of return to aggregate spending for agricultural research with the hurdle rate for public expenditures suggests whether too little resources are being allocated to research. If the rate of return to agricultural research exceeds the hurdle rate, then social welfare could be enhanced by devoting more resources to research but at the expense of other investment activities that yield a lower rate of return. For a predetermined budget, estimates of rates of returns to different components of the budget can be used to rank the components accordingly. If the marginal rate of return to basic research was found to be higher than applied research, for example, it would imply that efficiency could be increased by reallocating some research from applied to basic research. Less money for applied research should drive up the marginal return of remaining funds (assuming they were spent in the most productive areas), while more money for basic research would drive down its marginal rate of return. At some point the returns to each would be equal, implying a more efficient allocation of the existing budget for research.

Using the Rate of Return to Make Research Funding Decisions

The rate of return for a conventional investment would, in its simplest application, be compared against the interest rate a firm must pay on funds borrowed to pay for the investment. For several reasons, the social rate of return to research has a less direct interpretation. Issues include:

- ***Past research.*** The return to past research, as measured in most studies, applies to current decisions only if research system performance will be the same in the future. An important aspect of this is that scientific opportunity continues to expand as technology advances. Some people have argued that scientific opportunities may gradually be exhausted, but there is little evidence to support this idea.
- ***Different decision rules.*** A firm makes decisions based on the rule that the estimated rate of return for a project must exceed the borrowing rate to be economically justified. Society's decision rule is more complicated because: (1) raising tax revenues creates distortions in the economy, which are extra costs termed "deadweight losses" by economists, and (2) the appropriate "social discount rate" on which to base public decisions is not directly observable. A risk-free, real (inflation-adjusted) market rate of interest is one standard of comparison. On this basis, the appropriate rate is usually estimated to be between 3 and 5 percent. Intergenerational equity is also a component of the social discount rate, but this component is not revealed by the market rate. Conceptual problems arise if public investment decisions are based on one rate while the private sector's are made based on a different rate.
- ***Measuring the rate of return.*** Economists seek to measure the marginal rate of return to research: that is, the return on the last dollar invested or on the last project funded. Conceptually, it is assumed that research funders align projects from the highest to lowest expected rate of return funds are exhausted. More accurately, the estimated marginal rate reflects the rate research managers would earn on another dollar of funding given the constraints under which they operate. This interpretation means that it may be possible to reallocate funding, remove constraints, or reorganize the research system and do better. A low marginal rate of return, therefore, may suggest a failure of the funding system rather than a lack of scientific or technological opportunity.
- ***Uncertainty and risk.*** Uncertainty introduces special considerations. A private firm may display risk aversion and demand a risk premium to undertake uncertain investments. A full portfolio of investments in the economy effectively acts as insurance, pooling the risks of many individual projects. Thus, public sector investments generally consider only the mean return and not special considerations for high risks. A second issue associated with uncertainty, however, is option value. Recent research on firm investment behavior has emphasized that uncertainty may introduce a value to waiting, which is referred to as option value. Committing investment to uncertain research eliminates the option to use the funds in some other way. This argument has been used to explain why firms demand a hurdle rate above their cost of funds. However, research investments generally expand the realm of possibilities in the future and thus increase society's options. This suggests that a conventionally estimated rate of return understates the value of research to society because these rates do not include the value of flexibility that research provides as options for an uncertain future.

The statistical estimates of the rate of return to research also provide evidence on the size of geographic and other spillovers from research. Spillovers from research are benefits captured by someone other than those who fund it. If there are spillovers from privately funded research to society, then the social rate of return to research will exceed its expected private rate of return. Since private funding decisions are based primarily on expectations of private returns, private companies will tend to underfund research if there are large spillovers. Spillovers from research are often larger for basic, or pre-technology, research and smaller for research and development activities closer to the commercialization stage. Estimates of spillovers can also suggest Federal versus State areas of responsibility for funding research. If the benefits from research accrue primarily to a single State, then that State will have an incentive to fund it fully. On the other hand, if research conducted in a State benefits neighboring States as well, then States may underinvest in research for the same reason a private firm might. Individual States may attempt to "free-ride" on neighboring States, hoping to benefit from technologies developed in neighboring States (Khanna, Huffman, and Sandler, 1994). So, research with larger geographic or national spillovers should be more a Federal rather than State responsibility. Statistical evidence has found cross-State spillovers from agricultural research to be large, especially for livestock research (Evenson, 1989).

The benefits from agricultural research are also shared globally. Foreign consumers benefit from U.S. research that lowers the cost of exported commodities. Foreign producers may also benefit from research conducted in the United States, and vice versa, although some adaptive research is usually required to transfer agricultural technology across geographic areas. Genetic improvements in agricultural commodities are particularly dependent on international technology transfer. Kloppenburg and Kleinman (1987) provided an empirical analysis of the dependence of U.S. agriculture on foreign centers of genetic diversity. U.S. support for international agricultural research, while primarily aimed at improving agricultural productivity in developing countries, can also bring important reciprocal benefits for U.S. producers. For example, the transfer of semi-dwarf wheat and rice varieties from Mexico and Asia to the United States resulted in significant yield growth for U.S. growers (Dalrymple, 1980). Because of the global interdependence in sources of improvement for agricultural technology, Ruttan (1986) emphasized the need to strengthen the institutions supporting international agricultural research.

Empirical Estimates of the Social Rate of Return to Agricultural Research

Empirical estimates of the social rate of return to public agricultural research have used two different approaches, an economic surplus approach and a production function approach. The economic surplus approach evaluates yield or productivity changes that can be attributed to research. Productivity changes are interpreted as shifts in the supply function for an agricultural commodity. The supply shifts, in combination with econometrically estimated demand and supply elasticities, are the basis for estimating changes in consumer and producer benefits (that is, changes in consumer and producer surplus). The changes in consumer and producer benefits are compared with the cost of the research project (Norton and Davis, 1981). These studies have usually been conducted for individual innovations or individual crops where the productivity change can be more easily attributed to specific research funding. This approach requires assumptions about how research expenditures are allocated to specific productive improvements. Other assumptions are also required about when and for what period the benefits accrue. Some research investments cannot be clearly allocated. For example, allocation of basic research expenditures between specific products and innovations may be inappropriate since these expenditures may contribute to advances across, for example, multiple crops and many innovations.

The second approach relies on statistical estimation of production functions that contain R&D expenditures as an explanatory variable. These studies are usually more aggregated than the economic surplus studies. An advantage is that they do not require the judgment of the analyst to allocate research expenditures to specific innovations but rely on the statistical relationship revealed by the data. These estimates can control for other factors that may influence productivity and, thus, avoid incorrectly attributing productivity gains to R&D alone. Griliches (1963, 1964) was the first to apply this approach by including the education level of rural farm populations and public agricultural research and extension efforts as separate variables in a cross-regional agricultural production function for the United States.

Returns to Aggregate Investments in Agricultural Research and Extension

Most studies that have estimated the aggregate social rate of return to research consistently found rates of return between 40 and 60 percent (table 4). An exception is White and Havlicek (1979) who found a rate of return of 20 percent for aggregate research. Studies that have combined research and extension spending generally have found a lower rate of return to the combined total, roughly 20 to 35 percent, than when research alone was considered.

Some studies have explored the issue of whether the rate of return to agricultural research has declined over time. Some of these studies show lower rates of return for later periods than for earlier periods. Lu, Cline, and Quance (1979) estimated that the rate of return to agricultural research fell by 2 percentage points per decade between 1939 and 1972. Such a decline in the rate of return might be expected if research expenditures increased relative to the availability of technological opportunities to exploit. In other words, public funding was responding to the estimated high rates of return and moving closer to an economically optimal level of funding. Funding for agricultural research grew during 1950-1970. Such increases would be consistent with an interpretation that the funding level was gradually gaining on technological opportunity. However, public funding for agricultural research has been stagnant in real terms since the 1970's. The stagnation in funding might have driven up the rate of return, as opportunities for progress grew more rapidly than the ability to exploit these opportunities. Unfortunately, the long lag time between research expenditure and its payoff, improved productive efficiency, makes it difficult to test this hypothesis empirically.

Given the many measurement issues associated with estimates of the rate of return as discussed above, there are other possible explanations for a declining rate of return. One explanation is that the research funding system has become less effective at selecting the best projects. There may also have been biases in the measured rate of return that contribute to an apparent decline over time. If the research payoff profile has become

Table 4—Aggregate returns to public investments in agricultural research and extension

Study	Methodology	Time period	Annual rate (Percent)
Griliches, 1964	Prod. function	1949-59	35-40
Latimer, 1964	Prod. function	1949-59	[1]
Evenson, 1968	Prod. function	1949-59	47
Cline, 1975	Prod. function	1939-48	41-50
Huffman, 1976	Prod. function	1964	110
Peterson and Fitzharris, 1977	Economic surplus	1937-42	50
	“	1947-52	51
	“	1957-62	49
	“	1967-72	34
Lu, Quance, and Liu, 1978	Prod. function, R&E	1939-72	25
Knutson & Tweeten, 1979	Prod. function, R&E	1949-58	39-47
	“	1959-68	32-39
	“	1969-72	28-35
Lu, Cline, and Quance, 1979	Prod. function, R&E	1939-48	30.5
	“	1949-58	27.5
	“	1959-68	25.5
	“	1969-72	23.5
Davis, 1979	Prod. function	1949-59	66-100
	“	1964-74	37
Evenson, 1979	Prod. function	1868-1926	65
White and Havlicek, 1979	Prod. function	1929-72	20
White, Havlicek, and Otto, 1979	Prod. function	1929-41	54.7
	“	1942-57	48.3
	“	1958-77	41.7
Davis and Peterson, 1981	Prod. function	1949-74	37-100
White and Havlicek, 1982	Prod. function, R&E	1943-77	7-36
Lyu, White, and Lu, 1984	Prod. function	1949-81	66
Braha and Tweeten, 1986	Prod. function	1959-82	47
Yee, 1992	Prod. function	1931-85	49-58
Huffman and Evenson, 1989	Prod. function	1950-82	41

Note: R&E gives estimated rate of return to combined research and extension expenditures. Otherwise, estimate is for research alone.

[1] Not significant.

Sources: Economic Research Service compiled from Ruttan (1982), Echeverria (1990), Huffman and Evenson (1993).

longer over time, then some benefits of recent research may not have been allocated correctly or may not yet have been observed. There are also spillovers and complementarities of research through time. A shortfall of basic or fundamental research in one period may not affect productive efficiency in applied research for a decade or more. Much of the productivity growth of the past several decades was based on fundamental knowledge of genetics and chemical properties and improvements in machinery that originated in the 1800's. After decades of exploiting these gains in fundamental knowledge, one might expect some exhaustion of scientific opportunity. Biotechnology and computer technologies provide new basic scientific tools and insights that have not been widely exploited. The fundamental insights for these technologies date to the 1950's, but only in the past decade has there been much movement toward broad commercial application of products based on these insights. Thus, any apparent falloff in scientific potential may have been a lull rather than an inevitable trend. Still another possible explanation for a declining trend is that if, over time, more of the research was directed at nonmarket benefits such as environmental protection or human nutrition, these social returns may not have shown up in the measured rate of return.

While a declining rate of return may be due to a number of possible explanations, the evidence that the measured return has declined is weak. Evidence of a decline in the rate of return in Lu, Cline, and Quance (1979) is clearly inconsistent with some more recent studies (Yee, 1992; Huffman and Evenson, 1993; Braha and Tweeten, 1986) that include years through 1982-85. Comparing these later studies with earlier studies that include only years through 1960 (Griliches, 1964; Evenson, 1968; Cline, 1975) shows that both sets of studies obtain rates between 40 and 50 percent.

Returns to Research on Components of the Agricultural System

Besides studies of the aggregate rate of return, many studies have estimated returns to various components of the agricultural research budget. Separate estimates for different components of research provide evidence on whether the existing funds are allocated to yield the largest benefit. Redirecting funds from components with low marginal returns to those with high returns should yield a higher overall return. Research components considered in the literature include separate estimates for crops versus livestock and finer distinctions among commodities (table 5). Other researchers have compared the returns to research funding among basic (science-oriented) research, applied (technology-oriented) research, and extension and farm management research.

Most components of research spending show high rates of return, but estimates for individual components vary widely among studies. The wide variation provides little basis for strong conclusions about which components are more productive. Some studies (Bredahl and Peterson, 1976; Norton, 1981) found a higher rate of return

Table 5—Returns to components of public agricultural research

Study	Commodity	Period	Annual return (Percent)
Economic surplus approach:			
Griliches, 1958	Hybrid corn	1940-55	35-40
Griliches, 1958	Hybrid sorghum	1940-57	20
Peterson, 1967	Poultry	1915-60	21-25
Schmitz and Seckler, 1970	Tomato harvester	1958-69	16-46
Production function approach:			
Peterson, 1967	Poultry	1915-60	21
Bredahl and Peterson, 1976	Poultry	1969	37
	Dairy	1969	43
	Livestock	1969	47
	Cash grains	1969	36
Evenson and Welch, 1979	Crops	1964	55
	Livestock	1964	55-60
Evenson, 1979	Technology-oriented	1927-50	95
	Science-oriented	1927-50	110
	Science-oriented	1948-71	45
	Technology-oriented	1948-71	93-130
	Farm mgmt. and ext.	1948-71	110
Norton, 1981	Cash grains	1969	31-57
	Dairy	1969	27-50
	Poultry	1969	30-56
	Livestock	1969	56-111
	Cash grains	1974	44-85
	Dairy	1974	33-62
	Livestock	1974	66-132
Sundquist, Cheng, and Norton, 1981	Maize	1977	115
	Wheat	1977	97
	Soybean	1977	118
Smith, Norton, and Havlicek, 1983	Livestock	1978	22
	Dairy	1978	25
	Poultry	1978	61
Huffman and Evenson, 1993	Crops	1950-82	47
	Livestock	1950-82	<0
	Science-oriented	1950-82	74

Sources: Economic Research Service compiled from Ruttan (1982), Echeverria (1990), and Huffman and Evenson (1993).

for livestock research than for cash grains research, while Huffman and Evenson (1993) found the opposite. There is, however, some consistency in studies that found a higher rate of return to science-oriented (basic) research than for applied research.

The evidence on returns to extension is extremely varied (table 6). Some studies on aggregate research found a higher return when research spending was considered separately than when research and extension expenditures were combined, suggesting a lower return to extension (table 4). This evidence and the recent work of Huffman and Evenson (1993) suggest a rate of return to extension of roughly 20 percent, lower than for categories of research. However, another set of studies including work by Huffman (1976) and Evenson (1979) found rates of return to extension between 82 and 110 percent. While Yee (1992) did not publish a rate of return to extension, his estimated parameters for extension similarly show a rate of return about 100 percent. Evenson (1979) also found that a farm management research/extension component had the highest marginal return among the categories considered. There is no obvious pattern among these findings: high and low rates were found for earlier years and later years and estimated rates varied when the same authors evaluated returns using different methods. Nor is there a particular pattern where one methodology routinely produces high estimates while others produce low estimates.

There are particular problems for estimating returns to extension. Over time, a larger share of extension funding has involved family, rural community, and nutrition activities. Whatever the benefits of these activities, they will not be reflected in the agricultural sector's productive efficiency. Therefore, to measure the returns to these activities requires that other measures of success be used. The data-reporting system for public extension expenditures is also less systematic than that for research expenditures.

Table 6—Returns to extension

Study	Period	Annual return (Percent)
Lu, Quance, and Liu, 1978; Lu, Cline, and Quance, 1979	1939-72[1]	24-31
Evenson, 1979	1949-71	110
Huffman, 1976 and 1981	1964	110
Huffman and Evenson, 1993	1950-82	20
Evenson, unpublished	1950-82	82-101

[1] Combined research and extension.

Source: Economic Research Service compiled from Huffman and Evenson (1993).

For public research activities, a standard set of categories for reporting research expenditures has been in place for many years. However, extension spending categories have changed significantly over time. The researcher who wished to analyze extension returns must make a variety of assumptions to generate a consistent time series of extension expenditures that relate only to productive efficiency.

There is a potentially severe problem of spillovers from the private sector that may lead to an upward bias in returns to extension. Considerable effort has been directed toward controlling for private spillovers from research but this has not been possible for extension. There are many private sources of information that compete with extension, such as farm cooperatives and farm input suppliers (seed, chemical, machinery, computer software firms) that provide information on how to use their products to improve farm productivity. There is also a newer development: firms specializing in providing farm services, such as pest scouting and nutrient management. The major difficulty in measuring private sector extension services is that these information services cannot frequently be separated from the sales of inputs and products.

Two important caveats are necessary in interpreting returns to the components of research. First, the measured returns are marginal rates. The expectation is that marginal rates decline as more funds are allocated to a research component.[10] Reallocating funds from a low-return component to a high-return component would drive down the return on the high-return component and drive up the return on the low-return component. Second, there are obvious complementarities among these components. Continued high returns to applied research, whether conducted by the public or the private sector, eventually depend on advances in basic research and in fundamental knowledge. Similarly, continued advances in basic understanding will not generate economic benefits unless applied R&D lead to commercialization of products, services, or practices.

The Estimated Social Rate of Return: Summary and Further Adjustments

Most studies of the social rate of return to public investment in agricultural research have consistently found

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[10] Diminishing returns in one type of research can be offset by advances in knowledge achieved elsewhere. Over time, technological opportunities increase as fundamental knowledge increases.

high rates of return. Overall, the marginal rate of return seems highest for publicly supported basic, or pre-technology research, followed by applied public research, private research, farmers' education, and, finally, agricultural extension (table 7).

Some critics have suggested that the estimated rates of return may be biased upward (see Appendix). Six specific concerns include: (1) errors in estimates of the research lag; (2) failure to adequately take into account the contribution of the private sector to technology development and diffusion (spillovers from the private sector); (3) extra costs of funding research through general tax revenues (in economic terms the "deadweight loss" from taxes); (4) effects of farm programs that may create commodity surpluses and cause prices of agricultural products to diverge from their economically efficient levels; (5) negative environmental, health, and safety effects of new technology; and (6) extra costs associated with resource dislocation and adjustment. In the extreme, some studies have concluded that after adjusting for the upward bias, the rate of return to public agricultural research is comparable to that for other investments in the economy (Pasour and Johnson, 1982; Fox, 1985).

The results of new empirical work that addressed three of the above criticisms are presented in table 8. Our model considered possible research spillovers from the private sector, the extra costs of funding research through general tax revenues, and possible errors in the research lag. Our estimates suggest that studies significantly overestimate the rate of return if they fail to account for these factors. If none of these factors are included, then the estimated annual social rate of return to agricultural research between 1915 and 1985 was approximately 60 percent. After adjusting for these factors, the rate of return to all agricultural research was likely to be about 35 percent.

Table 7—Summary of social rates of return to agricultural research, extension, and education

Item	Core range	Full range
	Percent/year	
All public agricultural R&D	40-60	0-100
Basic public R&D	60-90	57-110
Private R&D	30-45	26-90
Agricultural extension	[1]	20-110
Farmer's schooling	30-45	15-83

[1] No evidence of a core range.

Sources: Economic Research Service derived from Ruttan (1982), Echeverria (1990), and Evenson (1993).

There is insufficient information to determine the net effects on the returns to research of the other issues raised, specifically effects of commodity programs, environmental externalities, and resource dislocation. Studies that have attempted to adjust for the effects of commodity program have often based these adjustments on simplified and generally unreasonable assumptions about how farm programs are managed (see Appendix). The net effect of new technology on the environment has not necessarily been negative. While the development of more intensive production methods may cause environmental degradation from the use of agricultural chemicals, it also reduces the need to expand production into environmentally sensitive lands. Furthermore, adjusting the rate-of-return estimates for environmental, health, and safety factors may not provide appropriate guidance for current research funding decisions. With environmental externalities, such adjustments would reflect pollution that was uncontrolled when the current technology was developed. However, these externalities now may be controlled through regulation, product approval decisions, and other environmental controls and not relevant for current research allocation decisions.

For resource adjustment, the effect of public agricultural research on labor displacement in agriculture is an unsettled question. Most research on agricultural machinery is conducted by the private sector. Sometimes public research may have contributed to labor displacement in agriculture (Schmitz and Seckler, 1970). However, other evidence suggests that the overriding factor contributing to the growth in average farm size

Table 8—Adjustments for biases in estimated rates of return

Adjustment	Central estimate	Range
	Number	*Percent/ year*
Unadjusted rate of return	60	55-65
Inclusion of private sector research	9	5-15
Tax collection (deadweight losses)	6	3-9
Longer research lag	10	0-20
Commodity program effects	n.a.	Negligible
Environment, health, and safety	n.a.	+/-
Structural adjustment, labor displacement	n.a.	+/-
Return after adjustment	35	

n.a. = Not available.

+/- = Effects could be positive or negative.

Source: Compiled by Economic Research Service as an extension of Yee (1992).

(and the decline in agricultural employment) in the United States has been the pull of higher wage, nonfarm jobs, rather than the push from new agricultural technology (Kislev and Peterson, 1982). It is also possible to have separate policies for providing for those who are disadvantaged. The primary goal of research is improving productivity and efficiency. Using R&D policy to try to correct income discrepancies could lead to more equitably distributed income, but at the cost of significantly slower productivity growth.

Policy Implications

Studies have consistently found that the net social returns to public agricultural research in the United States are high. Even after adjusting for possible upward biases in these estimates, the marginal social rate of return to public agricultural research is estimated to be at least 35 percent annually. The marginal rate of return to fundamental (pre-technology) research appears to be even higher, followed by applied public research, private research, farmer schooling, and agricultural extension. The estimated rate of return to agricultural research is high compared with estimates of the hurdle rate for public investments. The social discount rate or risk-free real rate of return is generally estimated to be between 3 and 5 percent. The return generally earned by investments elsewhere in the economy, another standard of comparison, is about 18-20 percent. It is likely that many more resources could be devoted to agricultural research before the marginal rate of return fell to either of these hurdle rates. Thus, agricultural research as a whole appears underfunded.

Comparing social rates of return for private versus public research also suggests that there is a unique role for public investment in agricultural research. The private sector often underinvests in agricultural research because only a share of the total economic benefits can be captured. This is most true of fundamental (pre-technology) research and is also true for applied research that generates important nonmarket benefits, such as environmental, social science, food safety, and nutrition research.

Empirical studies have also found evidence of large inter-State spillovers from agricultural research. Increases in agricultural productivity within a State result from research investment of both that State and of other States. One implication of inter-State spillovers is the need for Federal support in the financing of agricultural research. In determining the appropriate level of investment, policymakers at the State level may consider only the benefits to the State and ignore benefits that could be transferred to other States. Thus, the investment by States would generally be less than the socially optimal level of investment (based on returns to the Nation as a whole). This is the rationale for the requirement that State governments match Federal formula funds provided to State institutions for agricultural research. Spillovers also occur globally. U.S. support of international agricultural research can have important reciprocal benefits for American agriculture.

Incentives for Private Investment in Agricultural Research

Private expenditures for food and agricultural research tripled in real terms between 1960 and 1992. The growth in private research on biological technologies was particularly rapid. Both government policies and market forces have influenced private investment in agricultural research. An important market incentive has been the growing world demand for food and agricultural products. Global population and income growth have increased the demand for new agricultural innovations. Industry has also been attracted by new technological opportunities in biotechnology, made possible by earlier public investments in basic biological sciences.

Public policies affect private incentives to conduct research in several ways. Public investments in fundamental and pre-technology research create new commercial opportunities for private firms. Governments can increase incentives for private research by strengthening IPR's for new inventions. Stronger IPR's enable inventors to capture a greater share of the commercial value of their inventions, which encourages more investment in research. Other policies, such as environmental, public health, and food safety regulations, also affect private incentives to invest in research (though not as directly). Regulations change the cost structure of firms and influence consumer demand for final products. Consequently, they affect market incentives to develop new agricultural technologies and food products.

At least two sets of policies affect private investments in agricultural research: (1) intellectual property rights for biological inventions, and (2) environmental, health, and food safety regulations. Each type of policy involves a trade-off between competing objectives. While IPR's provide private companies with more incentives to conduct research, they also increase the market monopoly power of these firms. The extent to which IPR's have increased private agricultural research and the effects of IPR's on seed prices and scientific progress are reviewed. Regulations, while helping to correct certain market failures, also may raise production costs, reduce innovation, and adversely affect market structure.

Intellectual Property Rights for Biological Inventions

One major development in science policy over the past 25 years has been the strengthening of intellectual property rights for new biological inventions. Historically, appropriating the gains from biological inventions was difficult because the product of a biological invention, such as a new variety of seed or livestock breed, also provides the means to reproduce it. Furthermore, biological inventions were considered "products of nature," and, therefore, not subject to standard patent law. Inventors of new plant varieties and animal breeds may now obtain the same patent protection that had long been afforded to chemical and mechanical inventions.

The strengthening of IPR's for biological inventions has been controversial. While stronger intellectual property rights for biological inventions increase the incentive for private industry to invest in new agricultural technology, it also raises important policy questions: Will the incentive lead to more research and improved technology for agriculture? Who will capture the economic benefits from new technology? Will competition for and ownerships of patent rights reduce the exchange of scientific information needed for the long-term advancement of science? Answers to these questions are essential for designing effective science policy.

Establishment of IPR's for Biological Inventions

The U.S. Constitution grants Congress broad powers to "promote the progress of science and useful arts, by securing for limited times to authors and inventors the exclusive right to their respective writings and discoveries." The Patent Act of 1790 and its subsequent amendments established a system of intellectual property rights to encourage inventors and manufacturers to develop new industrial inputs and consumer products. Until recently, the patent system's principal contribution to agriculture was the protection it offered for mechanical and chemical inventions. Biological inventions, such as new plant varieties and animal breeds, were not patentable because they were products of nature. As a result, plant breeders in the private sector concentrated most of their efforts on hybrid seed technology. Hybrid seeds offer a natural form of protection for intellectual property since the yield of second-generation progeny of a hybrid declines markedly. Thus, farmers do not save their own seed but buy new hybrid seed each season. However, hybrid seed technology has been commercially successful for only a few crops, such as corn, sorghum, and sunflowers. Most other crops grown in the United States are produced using open- or self-pollinated seed.[11]

To provide an incentive for private firms to increase their efforts in crop improvement, Congress enacted special plant breeders' rights for new plant varieties.

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[11] Hybrid seed technology is technically feasible but currently not economical for many other crops, such as wheat, alfalfa, and soybeans. The unsuccessful attempt to develop commercial varieties of hybrid wheat in the United States is examined in Knudson and Ruttan (1988).

The 1930 Plant Patent Act (an amendment to the 1790 Patent Act) established a special category of patents for asexually reproduced plants. Plants reproduced asexually are genetically identical, or clones, to the parent plant. These are plants that are not grown from seed but from cuttings, and include many types of tree crops (fruits and nuts), sugar cane, and ornamentals. Tuber crops, however, were specifically excluded from the act. Under the terms of the Plant Patent Act, breeders are given proprietorial ownership of new varieties for 17 years. Seed crops were not included in the act because of concerns that sexually reproduced crops would not be true clones of the parent plant.

Protection for new varieties of sexually reproduced seed crops other than hybrids became available in 1970, when the Plant Variety Protection Act was passed. Improvements in seed technology allowed breeders to develop new varieties that maintained the characteristics of the parent plant. Under this act, breeders are awarded Plant Variety Protection Certificates for new varieties shown to be distinct, uniform, and stable. Hybrid varieties were excluded from the act because they lack stability over generations. A Certificate gives a plant breeder proprietorial ownership of a new variety for 17 years. Unlike Plant Patents, which are awarded by the Patent and Trademark Office of the Department of Commerce, Plant Variety Protection Certificates are administered by the Department of Agriculture.

In their original form, these acts offered relatively weak intellectual property protection for plant breeders. Courts interpreted the acts as only protecting exact copies of the varieties. Phenotype variations, or variations in plant appearance due to environmental conditions, were unlikely to be protected (Schmid, 1985; Stallman, 1986). Other plant breeders were also allowed to use the protected variety in their breeding programs. One concern was that this would not prevent "cosmetic breeding," in which economically insignificant changes are bred into a protected variety to claim a new variety. In addition, under the Plant Variety Protection Act, farmers were allowed to save seed for replanting and to sell part of their seed to other farmers. While these limitations helped assure the wide availability of new varieties, they also reduced the returns to private plant breeding and lowered the incentive for private companies to invest in varietal improvement.

The Plant Variety Protection Act was amended in 1994 to increase incentives for private plant breeders. Also, the amendment made U.S. law conform with international standards for plant breeders rights established by the International Union for the Protection of New Varieties of Plants (UPOV). These amendments increase the scope of protection offered by Plant Variety Protection Certificates. Farmers are no longer permitted to sell seed without a license from the owner of the variety, although they may still save seed for their own replanting. While the 1994 amendments affect only varieties released after April 1995, a recent decision by the Supreme Court (*Asgrow* vs. *Winterboer*) eliminated the farmer exemption for varieties released in earlier years. Also, a provision was added to extend the scope of the Certificates to include "essentially derived varieties." This provision is designed to protect breeders from cosmetic infringement (for example, superficial changes in appearance that do not increase its yield or value). "Essentially derived varieties" refer to how much change must be introduced before a variety is considered truly different from its parent varieties. However, the legislation is vague on how this is to be determined. The 1994 amendments also extended plant breeders' rights to 20 years and included protection for tuber crops (U.S. Congress, 1993).

Judicial action in the 1980's also significantly expanded legal protection for biological inventions, particularly those involving biotechnologies such as genetic engineering. In 1980, the U.S. Supreme Court ruled in *Diamond* vs. *Chakrabarty* that living material was patentable. This case involved a genetically engineered microorganism that can digest and break down crude oil. Although patents for biological process inventions had been awarded since the 1800's, the Patent and Trademark Office did not permit patents on living products because they were a "product of nature" and not subject to the statutory subject matter defined by the Patent Act.[12] In *Diamond* vs. *Chakrabarty*, the Supreme Court determined that a human-made microorganism is patentable subject matter as a "manufacture" or "composition of matter" (Office of Technology Assessment, 1992).

While the *Chakrabarty* decision applied specifically to microorganisms, subsequent rulings by the Patent and Trademark Office's Board of Appeals and Interferences extended this protection to include all plants and nonhuman animals. In 1985, in *Ex parte Hibberd*, the Board concluded that patents could be issued for all plants, including open-pollinated seeds. This includes seeds, plants, plant parts, plant genes, and tissue cultures. In 1987, in *Ex parte Allen*, the Board awarded a patent for a genetically modified oyster and established a policy of allowing patents for new, nonhuman animal breeds, genes, and traits. The first patent for a mammalian

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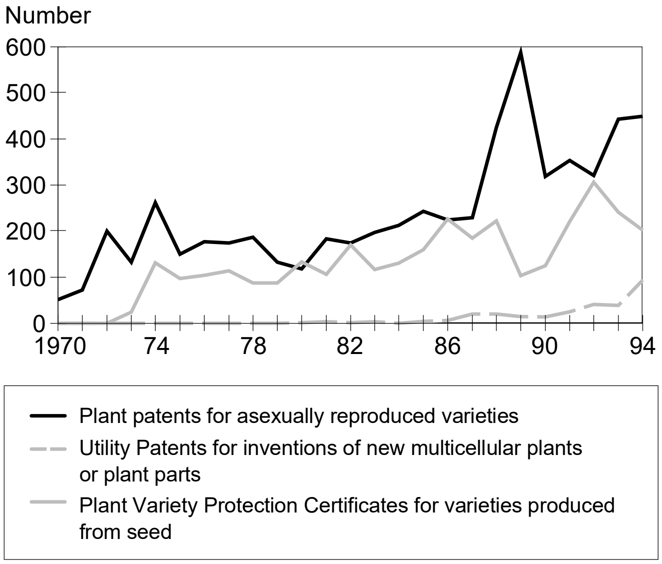
[12] The Patent and Trademark Office had previously awarded patents for compositions containing living organisms, such as microbial spores, yeast compositions, vaccines, and various dairy products (Office of Technology Assessment, 1992).

species, the genetically modified “Harvard Mouse,” was granted in 1988.

These decisions expanded the scope of intellectual property protection available for biological inventions. Patents awarded by the 1790 Patent Act (called Utility Patents) grant the owner broader powers of exclusion compared with plant breeders’ rights. For inventions covered by a Utility Patent, no one may make, use, or sell the invention without the permission of the owner. Biological processes and materials protected by a Utility Patent cannot be used by other researchers, except for purely academic or noncommercial research (Barton, 1993). For example, a new crop variety protected by a Utility Patent cannot be used in a breeding program without a license from the owner. The breadth of patent claims awarded for Utility Patents has generated considerable controversy in the research community.

Figure 7

Annual issues of intellectual property rights for new plants and plant varieties



Sources: Economic Research Service. Data derived from U.S. Department of Commerce, Patent and Trademark Office, CASSIS data base and USDA, *Plant Variety Protection Journals.*

There are now several options for protecting investments in biological inventions (table 9). Plant Patents grant proprietorial ownership for asexually reproduced plants and Plant Variety Protection Certificates are available for new varieties of seed crops. These ownership rights are restricted to specific varieties or close relatives and are generally called “plant breeders’ rights.” Awards of Plant Patents have experienced a general upward trend since 1980, with around 300-500 awarded per year by the early 1990’s (figure 7). Awards of Plant

Table 9—Intellectual property rights and private plant breeding

Coverage	Policy/action	Time	Application	Economic effects
Hybrid seed	Technological advances	1920	Corn	Large
	(protected by trade secret law)	1952	Sorghum	Large
		1968	Wheat	Small
Plant varieties produced asexually	Plant Patent Act	1930	Fruits, nuts, ornamentals	Small
Plant varieties produced from seed	Plant Variety Protection Act	1970	Field crops	Moderate
	PVPA amendment	1980	Vegetables	n.a.
	PVPA amendment	1994	Reduced exemptions	n.a.
	Supreme Court A v W	1995	Reduced exemptions	n.a.
Biological inventions	Supreme Court D v C	1980	Microbes	n.a.
	Ex parte Hibberd	1985	Plants	n.a.
	Ex parte Allen	1987	Animals	n.a.

n.a. = Not available.

A v W: *Asgrow* v. *Winterboer.*
D v C: *Diamond* v. *Chakrabarty.*

Source: Economic Research Service compiled from Griliches (1958), Butler and Marion (1985), Stallman (1986), and Knudson and Ruttan (1988).

Variety Protection Certificates for seed crops have remained steady over the past decade at about 200 per year. A stronger form of ownership rights, Utility Patents, can be used to establish ownership for specific plant and animal parts, traits, genes, and for new breeding and biotechnology methods. Utility Patents offer a broader scope of protection, and on average are of greater economic value for the owner. However, Utility Patents are generally more difficult to obtain since they require that the scientist show an “inventive step” (the nonobvious criterion). Since 1987, there has been a modest upward trend in awards of Utility Patents involving new plants, with 94 issued in 1994. Some Utility Patents are for specific genes or traits and may cover more than one variety or crop that expresses that trait.

Private Sector Investment in Plant Breeding

Private investment in agricultural research tripled in real terms between 1960 and 1992 (table 10). Private plant breeding underwent particularly rapid growth since the late 1960’s. By 1992, private companies spent an estimated $400 million annually for plant breeding research in the United States. Private firms have also invested heavily in modern biotechnology techniques. Agricultural biotechnology is applied not only to plant breeding, but also to food product development, livestock research, and biological pest control.

The private sector plays an important role in developing finished varieties for the major crop commodities. Between 1970 and 1994, 3,306 Plant Variety Protection Certificates were issued for new crop varieties, including 661 for soybeans, 322 for corn, 314 for wheat, and 211 for cotton (table 11 and fig. 8). Roughly 87 percent of the Certificates were awarded to commercial seed companies, with the rest going to public institutions.[13] By the mid-1980’s, private research had also expanded for secondary crops, including canola (rape), sorghum, and safflower. By 1989, nearly 900 scientists at the M.S. or Ph.D. level were engaged in plant breeding for private seed companies in the United States, an increase from about 700 in 1982. More than a third of these specialized in corn breeding (Kalton, Richardson, and Frey, 1989). However, for some small grains (oat, barley, and rice), the number of new private varieties developed remains low.

Of particular interest for policy is the extent to which the provision of plant breeders’ rights stimulated private investment in plant breeding. Economic studies have found mixed and uneven results (table 9). Assessments of the 1930 Plant Patent Act and the 1970 Plant Variety Protection Act suggest that the incentives for private plant breeding were uneven across commodities. Stallman (1986) found that the Plant Patent Act had little effect on private investment in fruit breeding.[14] High development costs of new fruit varieties and difficulties

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[13] These numbers do not include all the new varieties released for these crops over this period. The USDA and some land-grant universities do not seek Plant Variety Protection Certificates for their varieties, but instead make them freely available to seed companies for multiplication and sale to farmers.

[14] Currently, about a fourth of Plant Patents issued every year are for new varieties of fruits and nuts, and three-fourths are issued for flowers and ornamentals (American Association of Nurserymen).

Table 10—Private agricultural research expenditures by product areas, 1960-92[1]

Year	Food and kindred products		Farm machinery		Agricultural chemicals		Animal health		Plant breeding		Total agriculture[2]	Agricultural biotechnology[3]
	Mil. do.	*Pct.*	*Mil. do.*	*Pct.*	*Mil. do.*	*Pct.*	*Mil. do.*	*Pct.*	*Mil. do.*	*Pct.*	*- - - Million*	*dollars - - -*
1960	92	45	75	36	27	13	6	3	6	3	206	n.a.
1965	131	41	96	30	64	20	23	7	9	3	323	n.a.
1970	206	44	89	19	98	21	45	10	26	6	464	n.a.
1975	273	39	138	19	169	24	79	11	50	7	709	n.a.
1980	488	34	363	25	395	27	111	8	97	7	1,453	n.a.
1985	842	39	311	15	683	32	159	7	179	8	2,167	347
1990	965	32	360	12	1,127	37	245	8	314	10	3,012	516
1992	1,038	30	394	12	1,279	37	306	9	400	12	3,416	595

n.a. = Not available.

[1] Expenditures expressed in nominal dollars. [2] May not add due to rounding. [3] Agricultural biotechnology refers to the use of genetic engineering, tissue culture, monoclonal antibodies, and biosensors for food and agricultural purposes. These techniques are applied in several product areas, including plant breeding, food product development, and livestock research. To avoid double counting, research expenditures for agricultural biotechnology were not added with the other product areas in calculating total private expenditures for food and agriculture research.

Source: Economic Research Service calculated from Klotz, Fuglie, and Pray (1995).

Table 11—Plant Variety Protection Certificates issued for new crop varieties

	Certificates issued							Certificate ownership	
Crop	1971-74	1975-78	1979-82	1983-86	1987-90	1991-94	Total	Private	Public
	Number							*Percent*	
Field crops:									
Soybeans	34	69	132	150	114	162	661	84	16
Corn	0	1	6	50	104	161	322	100	0
Wheat	12	52	59	30	74	87	314	68	32
Cotton	24	35	41	38	34	39	211	87	13
Barley	0	12	2	22	6	35	77	82	18
Beans, field	0	1	5	18	10	28	62	77	23
Oats	0	10	6	0	9	8	33	36	64
Rice	0	8	4	2	5	15	34	100	0
Sorghum	0	0	0	0	2	31	33	100	0
Canola	0	0	0	2	8	15	25	72	28
Safflower	0	3	2	1	5	6	17	88	12
Other field crops	0	16	15	13	18	13	75	85	15
Total field crops	70	207	272	326	389	600	1,864	84	16
Grasses and forage crops:									
Fescue	0	5	16	28	38	30	117	90	10
Ryegrass	0	10	13	35	26	14	98	95	5
Alfalfa	0	3	22	16	30	11	82	84	16
Bluegrass	0	8	11	11	13	20	63	89	11
Other grasses	0	8	18	5	14	13	58	57	43
Total grasses	0	34	80	95	121	88	418	85	15
Vegetables:									
Peas	20	54	43	66	16	51	250	100	0
Beans, garden	31	39	20	29	21	70	210	100	0
Lettuce	13	16	14	17	32	70	162	100	0
Other vegetables	2	29	46	72	43	71	263	80	20
Total vegetables	66	138	123	184	112	262	885	94	6
Ornamentals	17	31	18	18	13	42	139	94	6
Total	153	410	493	623	635	992	3,306	87	13

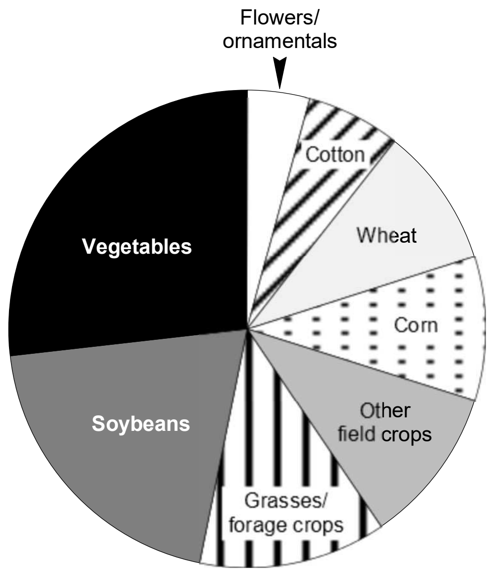
Source: Economic Research Service from U.S. Department of Agriculture, Agricultural Marketing Service, Plant Variety Protection Journals.

enforcing property rights constrained the profitability of private plant breeding for these crops. Perrin, Hunnings, and Ihnen (1983) found that, for some nonhybrid seed crops (particularly soybeans), private investments in plant breeding did increase significantly around the time of the 1970 Plant Variety Protection Act. For other crops, the incentives provided by the act seemed small. In a review of the economic effects of the Plant Variety Protection Act, Butler and Marion (1985) concluded that "the evidence . . . suggests the Act has resulted in modest private and public benefits at modest private and public costs" (p. 79).

One limitation of these studies is that they examined plant breeding efforts only until the late 1970's, less than a decade after the passage of the Plant Variety Protection Act. New investments in plant breeding often take several years to result in new crop varieties. Thus, these studies were not able to assess the effect of most new investments made once plant breeders' rights for seed became available. In a more recent study, Lesser (1994) found that Plant Variety Protection Certificates increased the value of New York soybean varieties about 2 percent. At this rate, according to Lesser, insufficient revenue would be generated to support much additional plant breeding by private firms. However, Lesser's results are limited to only one crop in one State.

Figure 8

Plant Variety Protection Certificates, 1970-94



Total = 3,306

Source: Economic Research Service. Data derived from USDA, *Plant Variety Protection Journals*.

Advances in basic biological science during the past 20 years have greatly expanded opportunities for applying biotechnology for agriculture. Biotechnology is being used to incorporate new traits in crops and livestock breeds. It is also being used to develop new livestock growth hormones and pharmaceuticals, biological pesticides, and food products (Caswell, Fuglie, and Klotz, 1994). The most important intellectual property right for biotechnology inventions is Utility Patents. As discussed previously, Utility Patents offer stronger protection than Plant Variety Protection Certificates or Plant Patents. Utility Patents may cover a trait that can be expressed in more than one commodity or species. As of December 31, 1994, 324 Utility Patents had been awarded for multicellular living organisms (table 12). Of these, 286 were for new plants or plant parts, and 38 were for animals. Most of the animal patents are for medical research purposes. About half the Utility Patents issued for plants involved recombinant, or genetically modified, varieties and cover a wide range of commodities. By far the most important use of Utility Patents has been for corn varieties, many of which are for inbred corn lines used in hybrid seed production.

Table 12—Utility Patents issued for multicellular organisms through 1994

Item	Patents issued
	Number
Technology[1]:	
Animal	38
Plant:	286
Plant, seedling, or plant part	154
Recombinant plant	103
Somatic cell fusion-derived plant	10
Mutant plant	25
Grafted plant	3
Total	324
Plant commodity[2]:	
Corn	83
Tomato	24
Tobacco	23
Soybean	17
Rice	15
Sunflower	10
Potato	9
Wheat	8
Canola	8
Cotton	8
Mushrooms	8

[1] A single patent may involve more than one technology or commodity. [2] Only commodities with eight or more patents are listed.

Source: Economic Research Service adapted from CASSIS database, Patent and Trademark Office, U.S. Department of Commerce.

Table 13—Ownership profile for Utility Patents

Owner	Private	Public	All
United States	204	48	252
Foreign	63	9	72
Total	267	57	324

[1] Includes patents awarded for multicellular organisms (patent class 800).

Source: Economic Research Service calculated using CASSIS database, Patent and Trademark Office, U.S. Department of Commerce.

The ownership of Utility Patents for plant inventions has been more diverse than that for plant breeders' rights for new varieties. Sixty-three percent of Utility Patents for multicellular organisms were issued to U.S.-based companies, compared with about 90 percent of the Plant Variety Protection Certificates (table 13). Twenty-two percent of the Utility Patents are owned by foreign companies or institutions, while 15 percent are owned by the U.S. Government or U.S. universities. While plant breeders' rights are issued for new varieties that are ready for sale, Utility Patents generally cover inventions that are still at a pre-commercial stage. Public institutions that own patents may grant licenses to private companies to develop them into marketable products. Licenses raise revenues for public research institutions and can also protect a company's investment in commercialization. In fact, companies may be unwilling to make such investments in product development and marketing unless they have an exclusive license to the patented invention.

The principal rationale for granting stronger patent rights over new inventions is to stimulate more research by private entrepreneurs. Thus far, few agricultural biotechnology products have reached the marketplace, and, consequently, little information exists on the economic effect of Utility Patents for agriculture. However, one indication of how biotechnology is being applied to agriculture is the number of permits issued for field testing genetically modified organisms. Researchers wishing to conduct field tests with genetically modified plants and organisms must notify and/or receive a permit from the Animal and Plant Health Inspection Service (APHIS) before the test. Genetically modified plant varieties have been developed and tested for herbicide tolerance, resistance to insect pests or viruses, quality characteristics, or for pure research (table 14). Corn received the most permits for field tests (76 permits), followed by tomatoes (74 permits). Nearly a third of the permits were for plants modified for herbicide tolerance. Field test permits were issued to chemical and pesticide companies, seed companies, biotechnology firms, food companies, and public institutions.

Economic studies have shown that possessing a biotechnology patent significantly increases a firm's market value. In an analysis of the 20 largest publicly traded biotechnology firms, Austin (1993) estimated that each biotechnology patent added, on average, about 0.7 percent, or $1.7 million, to the firm's stock value. Patents that were closely identified with commercial products increased a firm's value by 1.9 percent, or $4.7 million. In a more comprehensive study of 535 venture-capital biotechnology companies, Lerner (1994) found a significant correlation between the number of patents owned by the company and its valuation in venture financing. Lerner also found that broader patents (defined by the number of international patent classes to which the patent was assigned) were of much greater value to a firm. Asset valuation of venture-capital firms is a critical factor in determining access to continued sources of financing. It also enables them to raise revenue by licensing the patented invention to other companies. Utility Patents appear to have enabled firms to maintain their investments in biotechnology research, though few final products have yet reached the marketplace.

Neither Austin (1993) nor Lerner (1994) distinguished agricultural biotechnology patents from other kinds of biotechnology applications. Most of the firms investigated in these studies were in the pharmaceutical and medical industries. However, Lerner tested whether the value of patents differed among firms specializing in human therapeutics, human diagnostics, biotechnology research equipment, and agricultural or industrial applications, and found no significant differences in patent values. Additional evidence comes from a 1991 survey of agricultural research firms by Pray, Knudson, and Masse (1993). They received responses to a question-

Table 14—Field test permits issued for genetically modified plants, through June 1993

Crop	Herbicide tolerance	Insect resistance	Virus resistance	Product quality	Research	Total
				Number		
Corn	31	22	12	5	6	76
Tomato	11	15	13	27	8	74
Potato	2	7	39	10	6	64
Soybean	48	0	1	4	4	57
Cotton	25	14	0	0	0	39
Tobacco	6	11	9	3	6	35
Rapeseed	4	1	0	11	0	16
Alfalfa	3	0	8	1	0	12
Melon	0	0	10	0	0	10
Cantaloupe	0	0	10	0	0	10
Rice	1	2	1	1	2	7
Other	1	6	12	5	8	32
Total	132	78	115	67	40	432
Percent	31	18	27	16	9	100

Source: Economic Research Service compiled from Ollinger and Pope (1995).

Table 15—Selected mergers and acquisitions in the seed industry

- **Parent firm** (Type) [Nationality]
  - Subsidiaries (Year of acquisition)

- **Atlantic-Richfield** (petroleum) [USA]
  - Dessert Seed Co. (1980)
  - Castle Seed Co.

- **Cargill** (food) [USA]
  - ACCO Seeds (1980)
  - Dorman Seeds (1971)
  - Kroecker Seeds (1979)
  - P-A-G Seeds
  - Paymaster Farms
  - Tomco Genetic Giant

- **Celanese** (chemical: merged with Hoechst in 1987)
  - Celpril, Inc. (1975)
  - Moran Seeds (1974)
  - Joseph Harris Seed Co. (1978)
  - Niagara Farm Seeds (1980)

- **Ciba-Geigy** (chemical: merged with Sandoz, 1996) [Swiss]
  - Columbiana Farm Seeds (1973)
  - Funk Seeds International (1976)
  - Germain's
  - Hoffman
  - Louisiana Seed Co. (1976)
  - Peterson-Biddick
  - Shissler
  - Steward Seeds (1974)
  - Swanson Farms
- **George J. Ball** (seed) [USA]
  - Denhold Seeds
  - Pan-American Seeds
  - Petoseed
- **Hoechst** (chemical) [German]
  - Canners
  - Hild
  - Nunhems
- **Imperial Chemical Industries** (chemical) [British]
  - Cotinseed (1985)
  - Grast (1985)
  - Miln Marsters (1985)
  - SES (1985)
  - Sinclair McGill (1985)
- **IT&T** (telecommunication) [USA]
  - Moran Seeds (1978)
  - W. Atlee Burpee Co. (1978)
- **Limagrain** (seed) [France]
  - Ferry-Morse (1981)
  - Shissler
  - Tozier
  - Vilmorin

- **Lubrizol** (chemical)
  - Agricultural Laboratories
  - Arkansas Valley Seed
  - Colorado Seeds
  - Gro-Agri
  - Jacques Seed (1985)
  - Keystone Seed Co.
  - Lynville (1985)
  - McCurdy Seed
  - R.C. Young
  - Seed Research Associates
  - Sigco (1985)
  - Sun Seeds
  - Taylor-Evans Seed Co.
  - V.R. Seed
- **Monsanto** (chemical) [USA]
  - Hybritech Seed International
  - Jacob Hartz Seed Co. (1983)
  - DeKalb Hybrid Wheat (1982)
- **Occidental Petroleum** (petroleum: merged with Sandoz, 1983)
  - Excel Seeds (1972)
  - East Texas Seed Co. (1973)
  - Missouri Seeds
  - Moss Seed Co. (1972)
  - Payne Brothers Seed Co. (1973)
  - Ring Around Products (1978)
  - Stull Seeds (1975)
  - West Texas Seed Co. (1975)
- **Royal Dutch/Shell** (petroleum: merged with Dupont in 1986)
  - Agripro Inc. (1980)
  - Ferry-Morse, Farm Seed Division
  - H.P. Hybrids (1979)
  - Nickerson American
  - North American Plant Breeders (1973)
  - Rudy Patrick (1974)
  - Sokota Hybrid Producers Assn.
  - Tekseed Hybrids (1979)Celpril
- **Pfizer**
  - Clemens Seed Farms (1975)
  - Jordan Wholesale Co. (1975)
  - Ramsey Seed
  - Trojan Seed Co. (1975)
  - Warwick Seeds
- **Sandoz** (chemical; merged with Ciba-Geigy, 1996) [Swiss]
  - Gallatin Valley Seed Co.
  - Hilleshog (1976)
  - Ladner Beta
  - McNair Seeds (1980)

Continued—

Table 15—Selected mergers and acquisitions in the seed industry—cont'd

Parent firm (Type) [Nationality]
Subsidiaries (Year of acquisition)

Sandoz—cont'd
- Northrup King (1975)
- Pride Seeds
- Rogers Brother Seed Co. (1974)
- Sluis & Groot (1976)
- Stauffer Seed (1976)
- Vaughans (1976)
- Woodside Seed Growers (1974)

Stauffer (chemical: merged with ICI in 1985)
- Blaney Farms (1979)
- Prairie Valley Seed Co. (1978)
- Rauenhorst, Bellows & Assoc. (1980)

Upjohn (chemical) [USA]
- Asgrow (1972)
- Associated Seeds (1972)
- Bruinsma (1968)
- Farmers Hybrid Seed Co. (1975)
- O's Gold (1968)

Sources: Economic Research Service compiled from Doyle (1982), Butler and Marion (1985), Kloppenburg (1988) and various trade journals.

naire from 90 companies with plant breeding and/or agricultural biotechnology research programs. Fifty-two percent of the respondents said that the availability of Utility Patents increased their ability to profit from research. Ten percent of respondents said it decreased their ability to profit, presumably because other companies that own patents can restrict access to scientific information and germplasm.

IPR's, Seed Monopolies, and Scientific Progress

The legal establishment of a system of intellectual property rights reduces market failures that result because some forms of knowledge cannot be appropriated. However, it creates a market failure resulting from a limited monopoly. During the life of a patent, the owner will encourage the use of the invention, at a cost, to reap some benefits of the invention. However, under a monopoly, the use of the invention will generally be less than if it were freely available. Thus a patent system reduces the social value of the invention, although it is preferable to having no invention at all. Legal protection of intellectual property provides a means of encouraging profit-oriented firms to allocate resources to research activities, although it achieves this at a social cost.

The tension between these two types of market failures underlies much of the public policy debate about intellectual property rights. How these rights are defined and enforced carries implications for both economic efficiency and equity. Inventors often favor stronger intellectual property rights so they may obtain the largest possible share of the social benefits of their invention. Users of the invention, on the other hand, seek to limit the monopoly power of the patent to increase the availability and reduce the cost of using the invention. The monopoly power afforded by a patent depends upon its duration and the breadth of exclusion given to the owner.

IPR's and the cost of seed. The extension of intellectual property rights for new crop varieties and biotechnology inventions raised concerns that it would enhance the market power of private seed companies and result in higher seed costs to farmers. These concerns were exacerbated by a series of mergers and acquisitions that took place in the seed industry beginning about the time the Plant Variety Protection Act was enacted (table 15). The first wave of acquisitions and mergers occurred in the late 1960's and 1970's, when many large chemical, oil, and food corporations acquired many medium- and small-sized seed companies. Another wave of mergers occurred during the 1980's, when many of these food, oil, and chemical companies sold their interests to agricultural chemical firms. While these changes to market structure reduced the number of independent seed companies, it also stimulated an infusion of new capital for plant breeding and biotechnology research. Large, multinational corporations had greater access to research resources and could sustain greater risks than small, independent companies (Chandler, 1990). Furthermore, agricultural chemical companies could achieve economies of scale in research and marketing by using synergies between biological and chemical technologies.

Table 16—Seed sales, private plant breeding, and trends in seed prices and yields, major field crops

Crop	Seed sales	Private plant breeding[1]	Seed cost	Share of seed purchased	Growth in seed price[2]	Annual growth in crop yield[2]
	Million 1989 dollars	Million 1989 dollars	Dollars/acre	Percent	Percent	Percent
Hybrid seed:						
Corn	1,031	112.9	21.09	95	4.75	1.33
Sorghum	90	12.6	5.13	95	5.08	1.54
Non-hybrid seed:						
Wheat	256	13.5	8.92	40	.97	1.13
Soybeans	610	24.9	12.03	73	1.92	1.23
Cotton	108	4.6	14.93	74	4.46	2.23

[1] Private research investment derived from Kalton, Richardson, and Frey (1989). [2] Average annual rate of growth in seed price and crop yield between 1975 and 1992. Annual seed price is divided by crop price to account for inflation.

Sources: Crop yields, crop prices, and seed prices were compiled by Economic Research Service from U.S. Department of Agriculture, *Agricultural Statistics*, various issues.

So far, there is little evidence that the changes in the structure of the seed industry have been detrimental to market efficiency or performance. Yields increased at an average annual rate of 1.0-1.5 percent for major field crops between 1975 and 1992, except for cotton yield, which increased at more than 2 percent per year (table 16). Probably about half of this yield growth can be attributed to improved varieties of seed (see box, "Contribution of Plant Breeding to Agricultural Productivity Growth"). Over this period, the real price of seed (measured as the ratio of the nominal seed price to the crop price) generally grew at a faster rate than yields. Prices for hybrid seed (corn and sorghum) rose more rapidly than prices for self-pollinated seed. Since farmers must repurchase hybrid seed each year, commercial seed companies are best able to capture the gains from varietal improvement for these crops. For self-pollinated crops, like wheat, some farmers save part of their crop as seed for the following year. Eventually, farmers purchase new seed even for these crops because of a breakdown in disease resistance, deterioration in uniformity, or the development of new, improved varieties.

Provided there is sufficient competition in the seed industry, seed companies will be unable to capture the full economic value of improved seed. They need to price their seed so that farmers will adopt their varieties. Otherwise, farmers could continue using old varieties or purchase seed from another company. For crops grown with hybrid seed, like sorghum and corn, seed companies appeared to capture only 35 to 48 percent of the value of improved seed, with the remainder going to farmers (fig. 9). For nonhybrid crops (wheat, soybeans, and cotton), seed companies obtained even lower shares of yield gains, from 12 to 24 percent. For the hybrid seed crops, seed companies invested over 10 percent of seed sales in research. For the nonhybrid crops, only 4 to 5 percent of seed sales were reinvested in research. The inability to capture a larger share of the gains from breeding nonhybrid crops served as a disincentive for seed companies to invest more in research.

Private incentives for investing in biological technology, such as plant breeding, appear to be less than those for manufacturing or chemical technology. Mansfield and others (1977) estimated that manufacturing firms capture about 50 percent of the gains from their research investments. Seed companies, on the other hand, appear to capture less than 25 percent of the gains from plant breeding of nonhybrid crops and between 33 and 50 percent of the gains from improved hybrid seed. The inability to appropriate these gains is a major reason the private sector tends to underinvest in research. Continued public support of applied plant breeding may be necessary to assure adequate investment in biological research.

IPR's and the progress of biological science. Some scientists and legal scholars have argued that the patenting of biological inventions could constrain varietal improvement and slow the rate of growth of the biotechnology industry. Varietal improvement and scientific advancement in biotechnology are largely an incremental process relying on past developments. For example, having ready access to the rice germplasm pool helped raise rice yields in the United States by 149 percent between 1950 and 1990 (Plowman, 1993). In the pedigree of the rice variety Lemont, the most widely grown variety in the United States, each of the parent varieties contributed one or more important traits (fig. 10). Restricted access to any one intermediate variety or contributing patent-

Contribution of Plant Breeding to Agricultural Productivity Growth

Before 1930, crop yields in the United States increased at a rate of less than 1 percent per year. With the development of new breeding methods, increased use of fertilizers and chemicals, and other improvements, yields began to increase more rapidly—especially after World War II. Between 1940 and 1992, corn yields increased at an average annual rate of 3 percent, cotton and wheat yields by nearly 2 percent, and soybean yields by 1.3 percent. While part of this growth was due to more fertilizers and pesticides, better agronomic practices, and investments in irrigation and drainage, a large part can be attributed to plant breeding. Plant breeders developed new varieties, which used fertilizers more efficiently, increased pest resistance, and were better suited for local growing conditions.

Several previous studies have attempted to determine the contribution of plant breeding to yield growth in the United States. A recent study evaluated changes in the yield potential of sorghum, corn, soybeans, cotton, and wheat (Fehr 1984). This study found that between 1930 and 1980, the maximum yield potential of hybrid corn increased by 4.6 tons per hectare, or more than double the 1930 level. This is equivalent to 89 percent of the gain in corn yields achieved by Iowa farmers over this period. Sorghum yield potential increased by 1.6 tons per hectare, or 63 percent of the total change in average farmers' yields. For other crops, the study estimated that genetic improvement equaled 90 percent of soybean yield gains between 1902 and 1977, 67 percent of cotton yield gains between 1936 and 1960, and 50 percent of wheat yield gains between 1958 and 1980. The study compared the yield of old and new varieties in carefully controlled experiments that characterized intensive management conditions. This approach may overestimate the contribution of genetic changes to changes in farmers' yields since it does not take into account changes in the use of other inputs, such as fertilizers and irrigation. Farmers' yields are often below the maximum potential yield of a variety due to economic, management, and biophysical factors.

Thirtle (1985) estimated the contribution of biological inputs to the growth in farmers' yields, after accounting for changes in fertilizer, labor, machinery, and land use and allowing for substitution among inputs. Biological inputs include the use of improved varieties and changes in agronomic practices. Thirtle (1985) estimated that between 1939 and 1978, biological inputs increased corn yields by an average of 1.7 percent per year, wheat yields by 1.5 percent, soybean yields by 1.1 percent, and cotton yields by 0.5 percent. Compared with total yields realized by farmers over this period, biological inputs accounted for 50 percent of the yield growth in corn, 85 percent for soybeans, 75 percent for wheat, and 24 percent for cotton. Other studies using a similar methodology have estimated that genetic improvement in wheat contributed to about 50 percent of yield gains over roughly the same period (see Dalrymple 1980, p. 111, for references).

These estimates vary considerably for different crops and for the same crop during different periods. Technological advances often occur unevenly. Occasionally, a major technological breakthrough results in rapidly increasing yields for some years, but then yield growth slows until another major advance takes place. The discovery of economical methods of hybridization led to dramatic increases in corn yields after the 1930's that have continued up to the present time. Sorghum yields doubled in the 1960's when hybrids were first introduced, but yield growth has slowed since then. The introduction of semi-dwarf wheat and rice varieties helped to raise the yields of these crops in the 1960's and 1970's rapidly. Cotton yields increased dramatically in the 1950's, were stagnant between 1960 and 1980, and since 1980 have achieved steady increases. Plant breeding, like all research endeavors, is an uncertain and risky undertaking in which successes are difficult to predict.

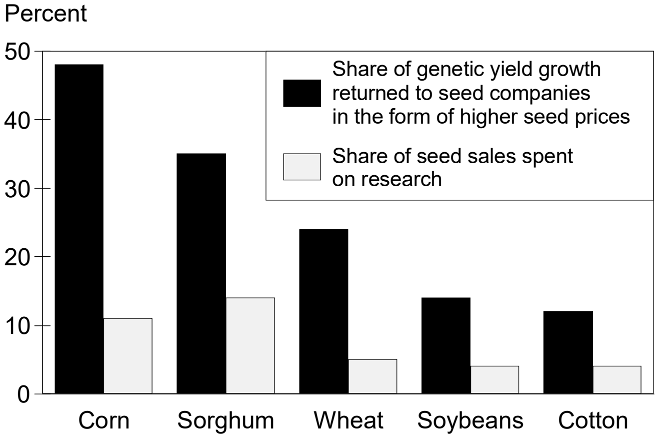
able technologies might have slowed progress in the development of this rice cultivar.

Restricted access to new technology is of particular concern for Utility Patents with broad claims. In a patent application, an inventor lists claims to indicate the scope of the invention. Patent claims stake out the technologies that the inventor controls. Obviously, it is in the inventor's interest to have as broad a claim as possible, as this increases the value of the patent. The patent examiner decides which claims are allowed. As a rule, the patent examiner must prove that a particular claim exceeds the information revealed by the invention to refute the claim. However, it is often difficult to determine the unique contribution of a particular invention from prior scientific advances. Significant overlaps can also arise between the claims of different patents. Once a patent is issued, narrowing of uncertain patent claims is left to the courts in particular infringement suits (Merges and Nelson, 1990). One difficulty in interpreting the claims of biotechnology patents is that, in biology, the structure-function relationships are not understood as well as mechanical and chemical technologies. The biotechnological inventive process is characterized by randomness and unpredictability. Applications of an invention or slight modifications of it can often be found in areas not envisioned by the inventor (Ko, 1992).

Questions about the patenting of new biological inventions are not only an issue for research conducted by

Figure 9

Appropriability and private research investment in plant breeding



This figure shows the share of genetic yield growth for these crops captured by seed companies in the form of higher seed prices and the share kept by farmers. To determine these shares, we first made two assumptions: (1) half of the growth in farmer yields can be attributed to genetic improvements and (2) the other half of the growth can be attributed to other factors. Then, we adjusted the change in yields for changes in seeding rates to get the increase in bushels of crop yield required to purchase one bushel of seed. The ratio of yield growth to genetic seed price growth gives the share of genetic improvement going to seed companies; the remainder is the share going to farmers. For example, between 1975 and 1992, corn yields grew by 4.78 bushels per bushel of seed planted. Assuming half of this increase is due to improved varieties implies a real yield improvement of 2.39 bushels per bushel of improved seed. Over the same period, the price of corn seed (in terms of the number of bushels of corn production needed to by one bushel of seed) increased by 1.16 bushels. Therefore, 48 percent of real yield growth was returned to seed companies in the form of higher seed prices. The remaining 52 percent was kept by farmers.

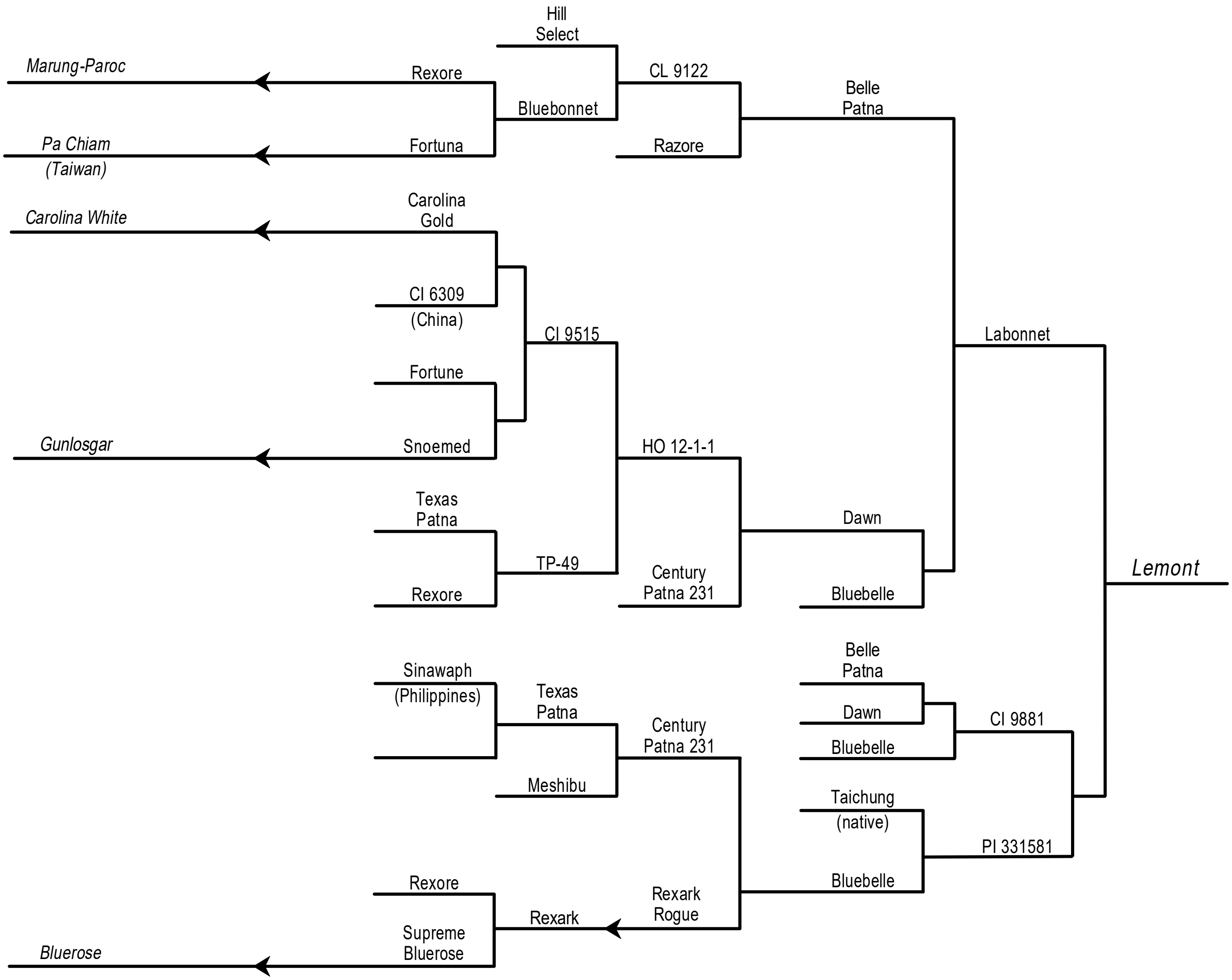
Sources: Economic Research Service. Data for crop yield, crop, and seed prices paid or received by farmers derived from USDA, *Agricultural Statistics* (seed prices normalized by crop price). Annual rate of growth in normalized seed price and crop yield is average between 1975 and 1992. Data for private research investment derived from Kalton, Richardson, and Frey (1989).

the private sector. Since the passage of the Patent Policy Act in 1980 (P.L. 96-517, also known as the Bayh-Dole Act), scientists conducting research supported by Federal funds have been allowed to own and license patents for their inventions. The intent of the legislation was to speed the rate at which basic scientific discoveries made at universities are developed into commercial technologies. Sometimes, it takes considerable additional investment to make a new invention into a commercially viable product. Firms may be unwilling to make these investments unless they have an exclusive license to the invention (Kitch, 1977). The law allows universities to own patents on discoveries made in federally funded research. Universities may then license their inventions to firms for commercialization. Patent licenses can be an important source of new revenue for the universities. However, patenting by universities could adversely affect the free exchange of information and materials among scientists as universities compete to be the first to achieve a new invention. Universities might be diverted into activities that are not compatible with their historical mission, which is “to protect and foster an environment conducive to free inquiry, the advancement of knowledge, and the free exchange of ideas” (Giamatti, 1982, p. 1278).

Empirical evidence on whether Utility Patents for agricultural biotechnology have curtailed scientific development is limited and mostly anecdotal. Surveys of agricultural scientists suggest that this may be more of a concern among researchers in the public sector than in the private sector. Public sector plant breeders have invested greater resources than their private sector counterparts in identifying major new traits and developing advanced breeding stock (Ruttan, 1982; Shands, 1995). Private seed companies have channeled more resources to incorporating advanced germplasm into their breeding lines and developing finished varieties (Ruttan, 1982). In a 1989 survey, 84 percent of directors of 49 State agricultural experiment stations thought that using patents in public research programs would adversely affect free exchange of plant germplasm between public and private breeders. Seventy-three percent thought that the use of patents in public research programs would adversely affect the free access and availability of undeveloped germplasm from international sources (Brooks, 1989). A 1991 survey of 90 agricultural research firms elicited their opinions about the effects of intellectual property rights on private plant-breeding programs (Pray, Knudson, and Masse, 1993). About 25 percent of respondents thought the availability of Utility Patents would reduce the flow of scientific information from government researchers and other firms. Thirty-five percent of respondents thought that exchange of germplasm would be curtailed. On the other hand, several respondents thought Utility Patents would serve to increase germplasm and information exchange, particularly among private sector firms. With patent protection, firms may be less inclined to rely on trade secrets to protect intellectual property. Twenty-five percent thought information would be more forthcoming from other firms, and 21 percent thought their competitors would be more likely to share germplasm. About 18 percent said that Utility Patents would

Figure 10

Pedigree of rice cultivar Lemont, indicating ancestors used to develop variety[1]



[1] Lemont is the most important rice variety currently grown in the United States.

Source: Economic Research Service. Data derived from Plowman (1993).

increase the flow of information and germplasm from government researchers to private companies. One limitation of this survey is that few biotechnology firms were included (only 5 of the 90 firms in the sample held Utility Patents).

There are several ways in which the patent process can be modified to reduce the likelihood of unduly restricting scientific development. One option is to have a broad research exemption for Utility Patents (Plowman, 1993). However, Karp (1991) maintains this would frustrate the reward and prospect functions of patents and seriously undermine the value of the patent system. A second option would be to require compulsory licensing of patents, based on a reasonable licensing fee (Tandon, 1982). A limitation of this option is the difficulty of establishing what is a reasonable fee. A third option would be to narrow the scope of patent claims (Merges and Nelson, 1990; Ko, 1992). This puts a heavier burden on the patent examiner, but there is some evidence that this is already occurring with animal patents (Lerner, 1994). A fourth option would be to leave the patent system as it is but encourage patent-pooling and cross-licensing. When exchanging germplasm, many seed companies and some universities use "material transfer agreements," which specify the terms of exchange.

These agreements typically require the recipient to use the material for research purposes only and not to transfer it to third parties. If the exchanged germplasm contributes to a new variety the recipient wishes to sell commercially, then the recipient and the supplier must negotiate a profit-sharing arrangement. Another version of patent-pooling and cross-licensing is a corn research consortium established in 1995 by the USDA, several State agricultural experiment stations, and about 20 private plant breeding companies. Under this agreement, the participants agreed to share breeding crosses (although not inbred lines) to promote the development of major new traits in the corn germplasm pool used for breeding finished varieties (Shands, 1995). Although firms have an incentive to license their patented technologies to one another, as a practical matter, these arrangements often involve high negotiation and transaction costs, particularly for major innovations. As a result, such arrangements are often not successful (for references to empirical studies on the transaction costs of patent-pooling and cross-licensing, see footnotes 146-148, p. 874, in Merges and Nelson, 1990).

Market Failure, Regulation, and Innovation

Market prices provide signals that guide private firms in their resource allocation and investment decisions. When prices for goods reflect their scarcity value to society, producers have an incentive to allocate resources in a socially beneficial manner. Sometimes, however, market forces fail to adequately convey societal values for natural resources or consumer preferences for products. The prices farmers pay for pesticides, for example, account for the resources used in pesticide manufacturing, but do not reflect environmental or health costs that may result from pesticide use. Food products may lack certain desirable characteristics, like improved nutrition, if consumers do not have adequate knowledge about them. Even if consumers were willing to pay more for products with such attributes, firms would have little economic incentive to develop them unless they could convey that information to consumers. Without additional incentives, the private sector will tend to undersupply new products and technologies when demand is not fully reflected in market prices.

Regulations are sometimes used to correct for inefficiencies that arise when market prices do not reflect social costs or values adequately. Regulations influence not only the production and supply decisions of firms. They also affect firms' R&D investment decisions. While regulations can help address market failures, they may also have detrimental impacts on the economy. They may significantly raise industry costs, reduce incentives to invest in R&D, and adversely affect market structure.

Regulation of Agricultural Biotechnology and Chemical Pesticides

New agricultural technology may have unintended consequences for the environment and human health. It has been known for some time that the application of some chemical pesticides to crops may adversely affect health and damage ecosystems. More recently, the arrival of biotechnology has raised concerns about potential environmental and health risks posed by genetically modified organisms. These concerns have led to increased Federal regulation of the agricultural chemical and biotechnology industries.

Agricultural biotechnology is currently regulated by Animal and Plant Health Inspection Service (APHIS) of USDA, the Food and Drug Administration (FDA), and the Environmental Protection Agency (EPA). APHIS regulates the field testing of genetically modified plants and organisms to guard against unintended environmental harm. Between 1987 and June 1993, 470 field tests of such organisms were conducted under the standards set forth by APHIS (table 14). As experience with field testing increased, these regulations were partially eased. In 1994, APHIS authorized the field testing of genetically modified varieties of corn, cotton, potatoes, soybeans, tobacco, and tomatoes without a permit if certain eligibility criteria and performance standards were met (although testers still must notify APHIS). Prior to commercialization, companies must also ensure that a genetically modified food product complies with State and Federal marketing statutes. These include State seed certification laws, the Food, Drug, and Cosmetic Act (FDCA), and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). The FDA, under authority granted through the FDCA, may regulate food products that may have been significantly altered by using plant biotechnology. The EPA may regulate plants that have pesticidal properties under authority granted through FIFRA (Office of Technology Assessment, 1992).

Regulation increases development costs and may delay the commercialization of new biotechnology products. On the other hand, some scientists consider these regulations insufficient for assessing the potential environmental risks posed by genetically modified organisms. While the APHIS regulations governing experimental testing appear to have been adequate for small-scale field trials, the information gathered from them may be deficient for evaluating the environmental risks of large-scale commercial use (Rissler and Mellon, 1993). Uncertainty and lack of consistency in the regulatory process can be impediments to the commercial viability of research investments in agricultural biotechnology.

Chemical pesticides have also been subject to increased regulation. Amendments to FIFRA enacted in 1972, 1978, and 1988 required companies to test new and existing pesticides for chronic and acute toxicity to humans and effects on fish and wildlife. The EPA was authorized to cancel or suspend pesticides that posed unreasonable environmental or health risks (Hatch, 1982).

In a recent study, Ollinger and Fernandez-Cornejo (1995) examined the effect of pesticide regulations on innovation in the agricultural chemical industry. The study found that these regulations significantly increased product development costs. Between 1972 and 1987, the cost of developing new pesticide products rose from $20.4 million to $54.2 million (constant 1982 prices). Much of this increase was to meet new regulatory requirements, such as evaluating chronic toxicity and assessing environmental effects on fish and wildlife. Between 1972 and 1991, regulatory costs rose from 18 percent to 60 percent of total R&D spending for agricultural chemicals (table 17). The study also found that regulations reduced the number of new chemical pesticide products available for use on minor crops. New pesticide registrations for vegetables, fruits, and nuts (minor-use pesticides) fell from 62 during 1972-76 to 15 during 1985-89. However, new registrations for major crops (corn, soybean, wheat, cotton, and sorghum) remained almost unchanged.

Although the regulations increased development costs and reduced product innovation, they also resulted in the development of pesticides with reduced environmental risks. These new pesticide products were often less toxic to nontarget species and would degrade more rapidly in the environment (Ollinger and Fernandez-Cornejo, 1995).

An unintended consequence of the pesticide regulations was their effect on the structure of the U.S. pesticide industry. Higher regulatory costs forced some companies to exit the industry. Regulations often favor larger and

Table 17—Structure and innovation in the agricultural chemical industry

	Firms[1]					Share of total R&D for:	
Year	Small	Large	Four-firm concentration ratio	Foreign firm market share[2]	New product registration for major firms[3]	Product development	Reregistration and testing
	Number	*Number*	*Ratio*	*Ratio*	*Number*	*Percent*	*Percent*
1972	16	17	0.496	0.18	12	82	18
1973	17	17	.501	.16	4	81	19
1974	17	17	.484	.20	11	82	18
1975	18	18	.487	.20	12	80	20
1976	18	18	.478	.21	7	67	33
1977	18	18	.441	.20	1	69	31
1978	18	18	.421	.22	0	71	29
1979	18	18	.407	.21	9	70	30
1980	16	18	.394	.21	9	71	29
1981	16	18	.378	.21	5	73	27
1982	15	18	.372	.21	7	70	30
1983	14	18	.392	.21	8	69	31
1984	10	19	.402	.23	7	72	28
1985	9	19	.385	.28	4	66	34
1986	8	18	.380	.29	8	61	39
1987	8	15	.454	.36	4	60	40
1988	8	15	.466	.38	4	59	41
1989	6	13	.483	.43	10	53	47
1990	n.a.	n.a.	n.a.	n.a.	3	45	55
1991	n.a.	n.a.	n.a.	n.a.	3	40	60

n.a. = Not available

[1] Companies in the sample introduced at least one new product between 1972 and 1989 or were among the top 20 companies by sales. [2] Includes production of foreign-owned plants in the U.S. plus imports by foreign owned companies. [3] Includes chemical pesticide registrations only. Major companies are firms ranked among the top 20 companies at least once between 1972 and 1991.

Source: Economic Research Service compiled from Ollinger and Fernandez-Cornejo (1995).

foreign-based companies over smaller domestic firms (Ollinger and Fernandez-Cornejo, 1995). The number of small pesticide companies in the U.S. market fell significantly after 1972 (table 17). Although the exit of some companies reduced the potential for innovation, the firms that remained tended to be those that were better able to operate in the more stringent regulatory environment.

The decline in new registrations of minor-use chemical pesticides has increased market opportunities for biological pesticides and genetically resistant crop varieties (Krimskey and Wrubel, 1992). A major environmental advantage of biological pest controls is that they often affect only one target species. However, they may be less effective than chemical pest controls in situations where crops are subject to multiple insect pests. Insect resistance is also a concern. A further constraint for some biological controls is that organisms that have been genetically modified for pest resistance are subject to the regulations governing biotechnology.

Food Standards and Product Quality

Consumer preferences for food products are based on product attributes such as taste, appearance, familiarity, and perceptions about nutritional value and safety. However, not all product characteristics are easily observable. Food grades and labels can be used to help consumers choose products by providing additional information on product quality. Labeling regulations may also affect the development of new products and processing methods with preferred attributes as firms respond to consumer demands for these characteristics.

USDA has authority over food inspections and has developed grading standards for many food products, such as meats, fruits and vegetables. USDA grading standards are voluntary, but producers, processors, and packers cannot use the USDA packaging label unless they adopt the USDA grading system. Grading systems are used to classify foods with dissimilar characteristics into groups with specific and more uniform food qualities (Office of Technology Assessment, 1992). Higher quality grades are priced accordingly.

A case study of the pork grading system showed that pork characteristics improved once the USDA grading system was put in place (Office of Technology Assessment, 1992). However, the study also found those grading standards can lag behind changes in consumer preferences. Consumer demand for leaner meat increased. However, grading standards continued to measure pork quality based on the firmness of the fat and lean muscle tissue and on the fat feathering in lean muscle (with more fat warranting a higher grade). As a result, new pork products with lower fat content would not yield a higher grade. This could discourage the development of leaner meat products unless new or alternative grading standards are adopted.

Food labeling is governed by the Food, Drug, and Cosmetic Act (FDCA) and by its 1990 amendment, the Nutrition Labeling and Education Act (NLEA). Under the FDCA, food producers have the option of labeling their products for advertising purposes voluntarily or to provide information to consumers about the attributes of a food product. The NLEA further requires producers to label all food and beverage products for nutritional content. FDA has regulatory authority over food labeling and may require companies to verify that these labels are not false or misleading. FDA can also require warning labels on products judged to have adverse health risks, such as those found on cigarette packages and alcoholic beverages.

Concerning genetically engineered foods, FDA decided against requiring a label simply stating that a food was "genetically engineered" since it would not provide substantive information to a consumer. The FDA determined that the safety of a food product should be judged based on its content and not by the process by which it was produced (Caswell, Fuglie, and Klotz, 1994).

Mandatory labeling requirements are designed to give consumers more comprehensive information about product quality and to provide an incentive to firms to develop new products with desirable characteristics. Zarkin and Anderson (1992) suggest that the new mandatory nutrition labels may induce producers to either reformulate existing products, develop new products, or change prices to increase sales.

In a study of the effects of food labeling, Ippolito and Mathios (1989) examined the effects of health claims for high-fiber cereals on consumer purchases and product innovation. Dietary fiber intake has been shown to reduce the risk of colon cancer. The study found significant increases in the consumption of high-fiber cereals and breads for certain segments of society because of health claim advertising. The growing demand for high-fiber cereals and the ability to make health claims on labels also induced cereal manufacturers to develop new high-fiber cereals. The increased focus on dietary fiber did not lead to changes in the sodium and fat content of high-fiber cereals, however. Moreover, companies are unlikely to invest in fundamental research to understand better the underlying links between diet, nutrition, and health (Caswell and Johnson, 1991). Public support for research may be necessary to expand knowledge in these areas.

Policy Implications

The private sector currently conducts more than $3.4 billion worth of food and agricultural research annually, much more than the public agricultural research system. These investments are driven by their perceived profit potential and are influenced by both market forces and government policies. Within the past 25 years, private agricultural research has moved beyond its traditional focus on food-product, mechanical, and chemical technologies to include biological technologies as well.

The ability of a private company to capture the gains from new technology is critical for encouraging private research investments. The strengthening of intellectual property rights for biological inventions provided an important stimulus for private investments in plant breeding and biotechnology. However, private incentives to invest in pre-technology research, such as the development of elite germplasm, are weak. Private investment in applied plant breeding also seems uneven across commodities, and is heavily oriented toward hybrid seed crops. Continued public support of applied plant breeding is likely to be necessary to sustain productivity growth for nonhybrid crops. Utility Patents with broad claims on biotechnology innovations have raised concerns that they may curtail longrun progress in biological science.

The regulatory environment also significantly affects the rate and direction of private research investments. Regulation of biotechnology field testing and pesticides has raised development costs for biological and chemical technologies. While these regulations reduce private incentives to invest in research, they also help direct research toward new products with desirable attributes, such as pesticides with less mammalian toxicity and less environmental persistence. Grading standards and labeling systems for food products can also encourage firms to develop new products with desirable characteristics, such as improved nutrition. However, standards and systems are unlikely to induce the private sector to undertake fundamental research on health and nutrition.

Public-Private Collaboration in Agricultural Research

Historically, the Federal-State agricultural research and extension system played a direct role in developing new technologies and encouraging their commercialization and adoption by farmers. Agriculture has been unique in this respect, compared with other sectors of the U.S. economy. The emergence of a strong private sector capacity in agricultural R&D has created new challenges and opportunities for the agricultural research system. There is now less need for the public research and extension system to provide finished technologies to farmers. This allows more public resources to be devoted to more fundamental, or pre-technology, research on scientific problems. However, an effective research system should be organized in a way that closely links basic and applied research. Otherwise the productivity of each may be adversely affected (Ruttan, 1982, 1983). Without institutional linkages between public and private research, R&D efficiency may decline and economic competitiveness suffer (Mowery and Rosenberg, 1989; Congressional Research Service, 1991).

In the 1980's, concerns that the U.S. economy was losing its technological edge in key industries led to new Federal policies. These policies encouraged public-private research collaboration and promoted rapid commercialization of new inventions. These policies included the Bayh-Dole Patent Policy Act of 1980 (P.L. 96-817), the Stevenson-Wydler Technology Innovation Act of 1980 (P.L. 96-48), and the Federal Technology Transfer Act of 1986 (P.L. 99-502). The 1980 Patent Policy Act allowed researchers to patent and issue exclusive licenses for technologies developed from federally supported research. The 1980 Technology Innovation Act and its subsequent amendment, the 1986 Technology Transfer Act, created an institutional mechanism for direct collaboration between government and private research laboratories—a Cooperative Research and Development Agreement (CRADA). USDA has been particularly active in using CRADA's to foster research collaboration between its research laboratories and private firms.

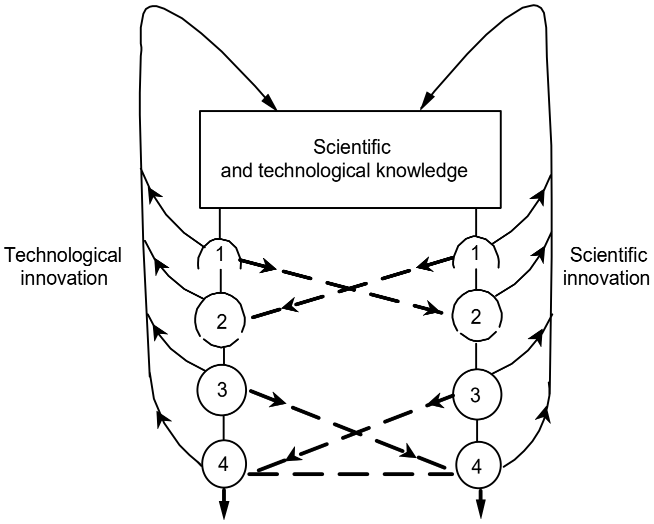
A Model of Science and Technology Innovation[15]

The traditional view of science and technology was that there is a direct linear relationship between advances in the two: progress in basic science led to the development of new technology (Bush, 1945). However, the interactions between science and technology are often more complex than this view suggests. Modern perspectives of the innovation process consider scientific and technological research to be two parallel but interacting paths (fig. 11). The two innovation paths are connected through the pools of existing scientific and technological knowledge from which both borrow and to which both contribute. Innovation along each path is imagined as a four-step process involving: (1) perception of a problem or incomplete pattern; (2) collecting research resources that can address the problem; (3) act of insight, when a solution to the problem is found; and (4) critical revision, in which newly perceived notions become more fully understood (Usher, 1954). In this process, science policy has most influence on step (2), where the scientific and technical resources are brought together to develop a solution to the problem. Step (3), the act of insight, entails a large element of uncertainty. This uncertainty makes it difficult to predict the timing and type of innovations.

The linkages and interactions between science and technology occur at all of the stages of the innovation process. For example, the development of a new alfalfa variety with enhanced nitrogen fixation involved contributions from science-oriented research in biochemistry,

Figure 11

Stylized model of scientific and technological innovation



Stage 1: Perception of the problem
Stage 2: Bringing together elements of a solution
Stage 3: Act of insight, which permits solution of the problem
Stage 4: Revision, refinement, and improvement

Source: Economic Research Service from Ruttan (1982).

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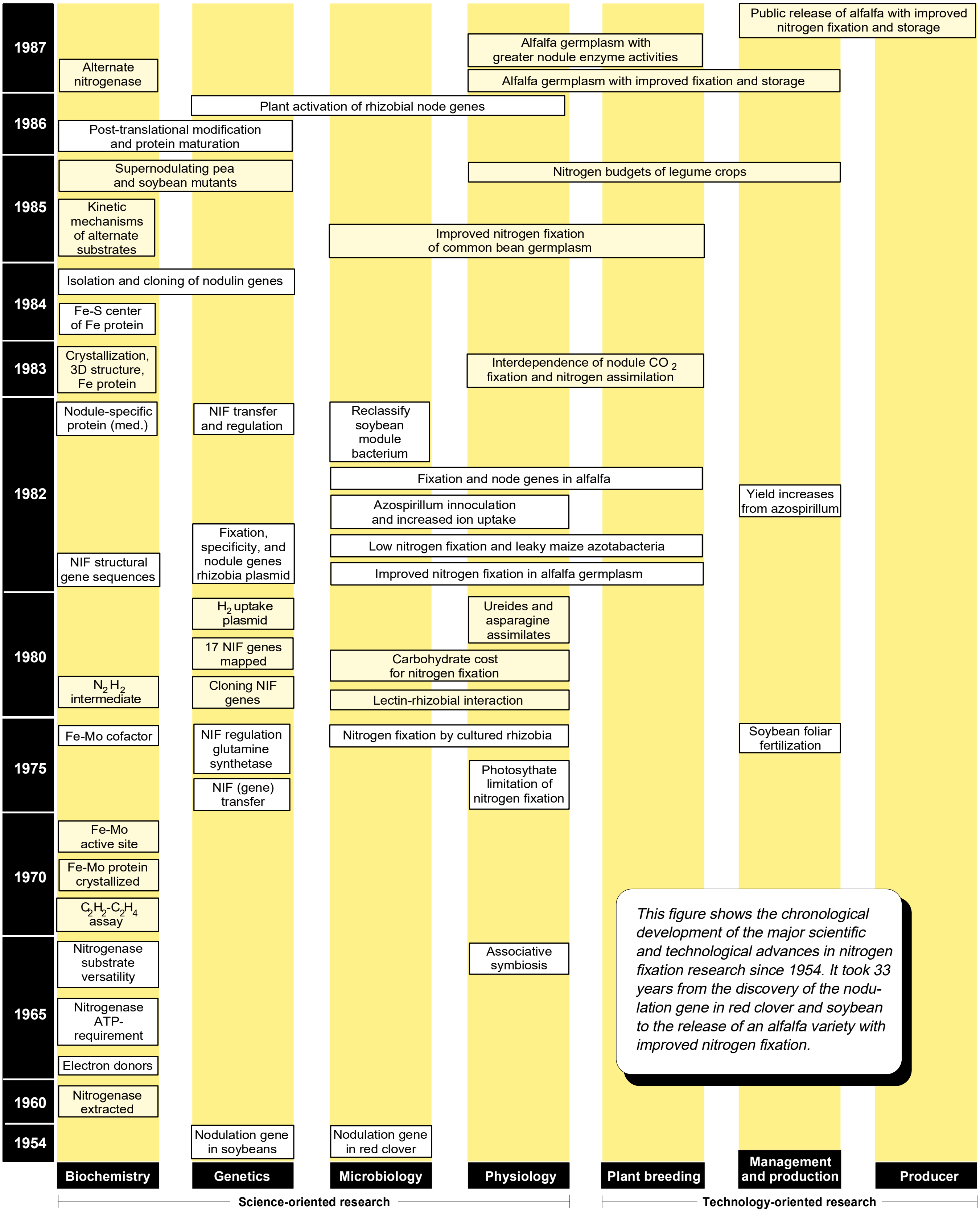
[15] This section draws heavily upon Ruttan (1982).

Figure 12

Science and technology breakthroughs in nitrogen fixation of a new alfalfa variety



This figure shows the chronological development of the major scientific and technological advances in nitrogen fixation research since 1954. It took 33 years from the discovery of the nodulation gene in red clover and soybean to the release of an alfalfa variety with improved nitrogen fixation.

Source: Economic Research Service adapted from Heichel, 1987.

genetics, microbiology, and plant physiology together with technology-oriented research in plant breeding and farm management (fig. 12). It took more than 30 years from the time science-oriented research identified the nodulation genes until technology-oriented research led to the release of the first alfalfa variety with enhanced nitrogen fixation. The effort relied on both disciplinary and cross-disciplinary research and interaction among scientists at several research institutions (Heichel, 1987).

Sometimes, a single individual or research team may occupy a leading position in advancing knowledge along both scientific and technical paths. In 1870, Louis Pasteur invented the modern science of bacteriology while he was trying to solve some practical problems involving wine fermentation and putrefaction. Commonly, however, leadership along each path proceeds at separate institutions and institutional partnerships are critical for success. In the 1920's, George Schull of the Carnegie Institute and Donald Jones of the Connecticut agricultural experiment station combined efforts. This led to the theory of hybrid vigor and the invention of the double-cross method of hybrid seed production. Presently, the close relationship between scientific (molecular genetics) and technological (genetic engineering) advances in biotechnology is also evident (Ruttan, 1982).

Effective institutional linkages between public and private research laboratories can increase the flow of both science-oriented and technology-oriented knowledge across the system. Private agricultural research is often more technology-oriented compared with public research. More than 40 percent of private agricultural R&D is for development research, compared with only 7 percent of public agricultural research. On the other hand, basic research is largely the responsibility of the public sector. Firms classify only about 15 percent of their agricultural research expenditures as basic research, compared with 47 percent of public agricultural research (table 18). The synergies between basic research and applied R&D suggest that effective linkages between public and private research laboratories can increase the productivity of both parts of the system.

Table 18—Shares of agricultural research expenditures devoted to basic, applied, and developmental research

	Type of research		
Source	Basic[1]	Applied[2]	Developmental[3]
Public	47.3	45.4	7.3
Private	15.0	43.5	41.5

[1] Basic research is conducted to determine the basic cause or mechanism of why certain results are obtained. [2] Applied research develops knowledge or information directly relevant to technology, to product development, or to market possibilities. [3] Developmental research generates a new or improved technology or product; supports market testing and introduction; maintains product performance and quality; or meets regulatory requirements.

Sources: Compiled by Economic Research Service. Public research data are for 1992 and from *Inventory of Agricultural Research,* USDA, 1993; private research data are for 1984 and from Crosby, Eddleman, Kalton, Ruttan, and Wilcke, 1985.

Public-Private Cooperation in Plant Breeding

Plant variety development is an area where there has been considerable discussion about the appropriate roles of public and private research (Ruttan, 1982; Knudson, 1990). Historically, the public sector was the dominant supplier of new varieties for field crops, while the private sector was the main source of new varieties for home garden and horticultural crops (Ruttan, 1982). For field crops, public sector plant breeders supplied foundation seed to private seed companies for multiplication and distribution to farmers. States enacted seed-certification programs to ensure that distributed seed was of appropriate quality. This pattern began to change in the 1930's when economical methods of producing hybrid corn became available. Hybrid seed technology offered a natural way to protect private investments in varietal improvement since farmers need to repurchase hybrid seed each season. The passage of the 1970 PVPA strengthened economic incentives for private research on nonhybrid crops as did *Ex parte Hibberd* in 1985.

The private sector is now making significant investments in plant breeding for most agricultural commodities. Between 1982 and 1989, there were significant increases in private plant breeding for corn, vegetables, soybeans, alfalfa, sugar beets, and canola (table 19). Both the number of companies and scientists engaged in breeding programs increased for these crops. Investments in wheat, sorghum, rice, and peanut breeding were stagnant over this period. While estimated nominal expenditures for these crops rose, the number of companies conducting wheat and sorghum breeding fell significantly and the number of breeders remained about the same. For cotton, sunflowers, safflower, and other small grains (oats, barley, rye, and triticale), private-sector investments in breeding declined. These adjustments reflect changing perceptions in the seed industry concerning the profit potential of its research investments. These perceptions are based on expectations about future growth in seed sales, the ability to protect intellectual property, and technological opportunities in biotechnology and plant breeding.

Table 19—Private plant breeding in the United States, 1982 and 1989

	Companies		Ph.D. breeders		Expenditures[1]	
Crop	1982	1989	1982	1989	1982	1989
	Number				*Million dollars*	
Corn	66	75	155	257	43.8	112.9
Vegetables	44	37	96	108	24.7	53.6
Soybeans	26	34	36	60	9.1	24.9
Wheat	21	11	23	25	6.7	13.5
Alfalfa/forage legumes	14	16	23	28	5.9	13.3
Sorghum	21	15	22	23	6.3	12.6
Sugar beets	5	10	14	22	1.7	9.8
Turf grass	8	16	9	8	1.7	5.9
Flowers/ornamentals	9	9	5	8	1.9	5.9
Sunflowers	16	9	15	7	4.1	4.8
Cotton	13	11	17	11	4.6	4.6
Rice	5	4	7	9	1.4	3.7
Canola	0	6	0	4	0.0	2.4
Oats, barley, rye, and triticale	11	6	7	5	1.5	2.3
Forage grasses	5	8	2	2	0.8	0.8
Peanuts	0	1	0	1	0.0	0.5
Safflower	3	2	2	1	0.4	0.4
Fruits	2	2	0	0	0.5	0.1
Total[2]	n.a.	n.a.	434	580	115.0	272.0

n.a. = Not available.

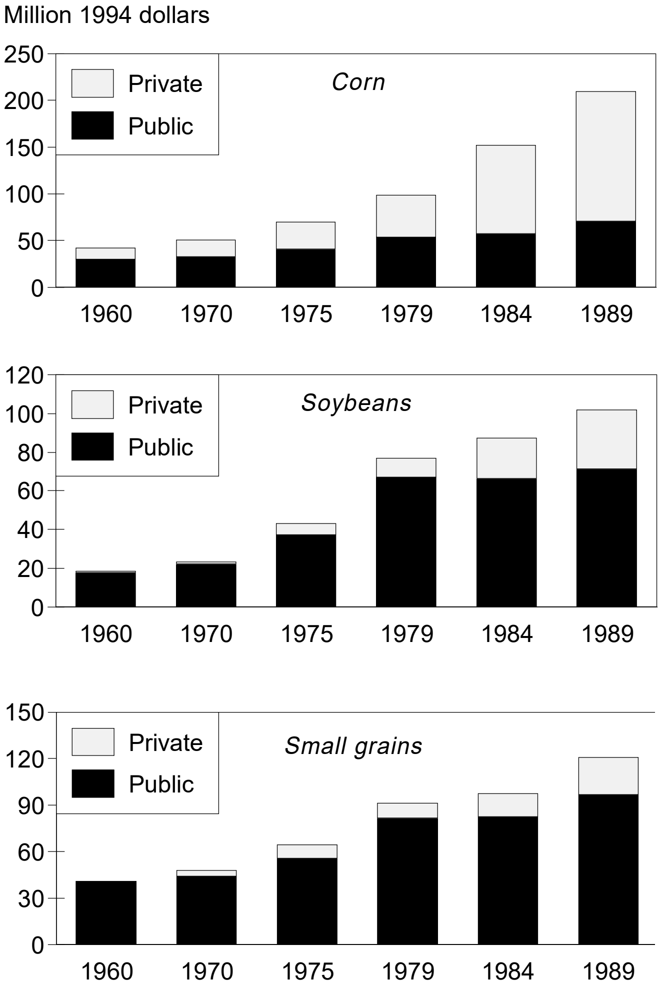
[1] Kalton, Richardson, and Frey (1989) only report an estimate of total expenditures for plant breeding. To compute expenditures for individual commodities, total breeding expenditure was multiplied by the proportion of all scientific full-time equivalents working on each crop. A weight of 1.0, 0.7, and 0.5 was given to each Ph.D., M.S., and B.A. scientist-year, respectively, to compute the proportions (see Kalton, Richardson, and Frey (1989) for complete data on scientist-years). [2] May not add due to rounding. The total number of companies participating in plant breeding cannot be inferred from this table since one company may breed many crops.

Source: Economic Research Service derived from Kalton, Richardson, and Frey, 1989. Private breeding for fruits and flowers is likely to be underestimated because breeding by individuals is not included.

The emergence of strong private breeding programs for some crops has affected the role and emphasis of public agricultural research. For hybrid corn, where the private sector can appropriate a large share of the gains from plant breeding, seed companies have invested heavily. By 1989, private seed companies accounted for more than 70 percent of total expenditures on varietal improvement for corn (fig. 13). Public sector programs moved to more pre-technology research, such as corn genetics and enhancing the germplasm pool used by private breeders (Ruttan, 1982). The Genetic Enhancement for Maize (GEM) initiative has established institutional linkages between public and private research in corn breeding. GEM is a consortium of Federal, State, and private seed companies designed to identify and introduce important new traits into the corn germplasm pool used to develop new varieties. The principal goal of the consortium is to screen and adapt exotic germplasm for use in corn breeding. Under the terms of GEM, the participants agree to share information and varietal crosses from exotic germplasm with other members. More than 20 private seed companies are participating in the consortium (Shands, 1995).

Since the late 1960's, private breeding in nonhybrid seed has increased significantly. In 1960, nearly all new varieties of soybeans came from public sector breeding programs (Huffman and Evenson, 1993). Private soybean breeding grew rapidly following the passage of the Plant Variety Protection Act in 1970. By 1990, the private sector had become the dominant source of soybean varieties, although it still provided only about 30 percent of total soybean-breeding expenditures. For small grains (wheat, rice, barley, oats, rye, and triticale), the public sector continues to be the most important source of new varieties. Much of the growth that occurred in private breeding for small grains in the late 1960's and 1970's was for hybrid wheat research. Hybrid wheat proved to have only limited commercial viability. As a result, many companies ended or reduced their

Figure 13
Public and private spending on plant breeding



Sources: Economic Research Service. Data for 1960-84 derived from Huffman and Evenson (1993); data for 1989 private research spending derived from Kalton, Richardson, and Frey (1989); and public research data derived from USDA, *Inventory of Agricultural Research*.

wheat improvement programs. Therefore, public wheat breeding continues to be an important source of finished varieties for farmers (Knudson and Ruttan, 1988; Knudson, 1990; Pray, Knudson, and Masse, 1993). Between 1975 and 1984, the share of private plant breeding for small grains fell from 20 percent to 15 percent of the total (fig. 13). While the overall capacity of the private sector to supply improved crop varieties has increased, it still may not be sufficient to maintain yield growth for several important field crops. The private sector continues to rely heavily on the public sector for pre-technology research.

Public support of research is justified when research is socially valuable but not profitable for private firms (the benefits are not appropriable). Fundamental research on improved breeding methods and the development of elite germplasm are areas that meet this criterion for investment by the public sector. For some crops, such as small grains, there appears to be no adequate incentive for the private sector to invest sufficiently in plant breeding. This is because private companies are unable to capture enough of the economic benefits from improved varieties. The 1994 amendments to the Plant Variety Protection Act may increase private sector research incentives for these crops. New advances in biotechnology breeding methods or hybrid seed technology would also encourage more private research by expanding market opportunities. Another reason for the public sector to maintain some capacity in applied plant breeding is to support its graduate education programs (Ruttan, 1982). Even with the growth in private sector plant breeding, universities will continue to be the main suppliers of scientific and technical staff to these companies. A continued presence by the public sector in applied research can also enhance market competition (Ruttan, 1982; Kloppenburg, 1988). If too few firms dominate the seed industry, lack of competition could result in reduced innovation. However, competition from the public sector can undermine the economic incentives provided by intellectual property rights. Currently there is little evidence to suggest a lack of competition among private seed companies (Butler and Marion, 1985). The role of the public sector in applied plant breeding needs to be periodically re-evaluated in light of developments in the private sector.

CRADA's:
Public-Private Collaboration in Research

Federal technology-transfer policy was given new impetus with the passage of the 1980 Stevenson-Wydler Technology Innovation Act and its 1986 amendment, the Federal Technology Transfer Act. These acts mandated that Federal research agencies should pursue technology-transfer activities with private firms. The 1986 Act established a mechanism, CRADA's, through which Federal and non-Federal researchers could collaborate. Before these acts, each Federal agency had its own method for disseminating technological innovations. The acts both mandated the "full use of the Nation's Federal investment in research and development" as well as provided an institutional structure to ease this transfer.

The 1986 Technology Transfer Act permitted Federal laboratories to enter into CRADA's with universities, private companies, non-Federal government entities, and others. A principal objective of a CRADA is to link the fundamental, or pre-technology, research capacity of Federal laboratories with the commercial research and marketing expertise of the private sector. Under a

CRADA, a Federal laboratory may provide personnel, equipment, and laboratory privileges. While the Federal agency cannot provide Federal funds to a cooperating institution, the collaborator may contribute funds directly to a Federal laboratory. The act also established rules regarding the ownership of inventions developed through CRADA's. The cooperating institution receives the right of first refusal to any joint discoveries and may be given exclusive access to data obtained in the research.

CRADA activity at USDA has increased rapidly since the program was first instituted in 1987. Between 1987 and 1995, USDA entered into over 500 CRADA's with private firms. In 1995, USDA had 227 active CRADA's with private companies, involving $61 million of public and private research resources in 1994 (table 20). CRADA's have been particularly important in seeking to develop new industrial uses for agricultural commodities (Glaser and Beach, 1993). USDA also received $1.6 million from patent licenses in 1995.

Table 20—USDA technology transfer activities

Year	Patents awarded	Patent license royalties	Active CRADA's[1]	Value of CRADA's[2]
	Number	*Million dollars*	*Number*	*Million dollars*
1987	34	.09	9	1.6
1988	28	.10	48	8.7
1989	47	.42	86	15.6
1990	42	.57	104	18.9
1991	57	.83	139	25.6
1992	56	1.04	160	30.0
1993	57	1.48	185	34.0
1994	40	1.43	212	61.3
1995	38	1.60	227	n.a.

n.a. = Not available.

[1] Cooperative Research and Development Agreements.

[2] Includes the value of USDA and private sector resources committed to CRADA's.

Source: Economic Research Service compiled from Office of Technology Transfer data, U.S. Department of Agriculture.

The role of CRADA's in furthering technological development can be illustrated with a brief case study of the development of the anticancer drug taxol.[16] Taxol is derived from the bark of the Pacific yew, which is a slow-growing relatively rare tree. Pacific yew bark was first collected in 1961. USDA collected samples as part of an interagency agreement with the National Cancer Institute (NCI) to search for anticancer agents. The active ingredient in taxol was isolated in 1971 but never patented. After revisiting taxol in the 1980's, the NCI decided that the substance was a promising drug and should be commercialized. Through a competitive bidding process, NCI signed a CRADA with the Bristol-Myers Squibb (Bristol) pharmaceutical company. The CRADA specified that NCI would give Bristol exclusive access to its clinical data.[17] Meanwhile, Bristol would give NCI taxol samples for trials and seek regulatory approval from the FDA for commercialization. Shortly after that, Bristol entered an agreement with the USDA and the U.S. Department of the Interior for exclusive rights to harvest Pacific yew trees on Federal lands. In exchange, Bristol would conduct research on alternative sources of the derivative for taxol and the environmental effects of harvesting the Pacific yew. In 1992, the FDA approved taxol for the treatment of ovarian cancer.

The NCI-Bristol CRADA provided a framework to link and coordinate an extensive array of cooperative research contracts. Bristol entered a complex set of research agreements with other public and private entities. These parallel research projects generated substantial basic scientific and technical information about taxol and enabled Bristol to access imperfectly tradeable assets, such as human capital. Bristol could use the expertise of universities and other firms without making long-term employment agreements. This was particularly important for university scientists who were willing to receive financial support from Bristol but wished to remain in academia.

A particular concern of the Federal government was the management of the Pacific yew tree, a relatively scarce natural resource. The NCI pursued several alternative technologies for synthesizing taxol by other means. USDA, for example, patented and licensed a means of producing taxol from tissue culture. This technology along with other new technologies have been successful at reducing the pressure on Pacific yew trees as the source for taxol. Bristol no longer harvests Pacific yews from public lands.

Access to exclusive information and data gave Bristol a substantial head start in the development of taxol and taxol-like drugs. This significantly reduced financial risks for Bristol and led to the rapid commercialization of the taxol drug. However, it also created potentially significant barriers to entry by rival firms. To enhance market competition and public access to taxol, NCI

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[16] This section is based on Day and Frisvold (1993).

[17] Amendments to the Technology Transfer Act were made in 1989 which exempted CRADA's from the requirements of the Freedom of Information Act for up to 5 years for Federally generated data and information.

continued research on alternative sources for taxol and on other taxol-like drugs. By pursuing alternative technologies, NCI helped assure its eventual commercial availability. Technology development programs sometimes fail because they consider a range of technological options that are too narrow (Cohen and Noll, 1991).

The taxol case study provides several policy lessons for technology-transfer activities. First, CRADA's can provide an effective institutional structure for coordinating research and development activities. The NCI-Bristol CRADA served as a unifying framework to connect an impressive array of sub-agreements between businesses, government agencies, and universities. Second, through fundamental and pre-technology research, Federal laboratories can contribute significantly to the rapid commercialization of new technology. Public research institutes helped reduce commercial risks faced by Bristol by generating new knowledge about taxol. Third, pursuing multiple paths to technology development can increase the likelihood of success and encourage market competition. NCI encouraged the exploration of many alternative paths for producing large-scale supplies of taxol.

Policy Implications

Formal institutional linkages between the public and private sectors in agricultural research are a relatively new undertaking. Such arrangements serve to more closely link together science-oriented public research with technology-oriented private research. Nevertheless, public-private cooperation in research raises new issues that have important social and economic consequences, such as the ownership of intellectual property and the content of the public research agenda. The nature and scope of public-private institution linkages in agricultural research are still evolving and warrant further analysis and discussion.

Appendix: A Critical Assessment of Estimates of Social Returns to Agricultural Research

Some critics have suggested that the estimated social rates of return to agricultural research may be biased upward. In the extreme, some have concluded that after adjusting for upward bias, the rate of return to public agricultural research is comparable to that of other investments in the economy (Pasour and Johnson, 1982; Fox, 1985). We address six specific issues that are potentially serious sources of bias in measured social rates of return to agriculture. These include (1) the research lag; (2) spillovers from the private sector; (3) the added costs to the economy of raising funds for research through taxation, or, in economic terms, the consideration of the "deadweight loss" associated with funding public expenditures through taxes; (4) biases because farm programs create commodity surpluses and may mean that the prices of agricultural products diverge from the economically efficient levels; (5) failure to account for environmental, health, and safety effects of new technology; and (6) failure to account for dislocation and adjustment costs.

Research Lags

The time lag structure of benefits of R&D expenditures is important because the sooner the research benefits are received and the longer they last, the higher the rate of return to research. Econometric estimation of research lags, while artificially truncating lags, usually forces a particular pattern of benefits that can lead to an under- or overestimate of the rate of return (Alston and Pardey, 1996). Studies that have specifically tried to estimate how long research may continue to affect productivity have found persistent effects for at least 30 years (Pardey and Craig, 1989; Schimmelpfennig and Thirtle, 1994).

Analysts have made various assumptions for approximating the complex lag structure of the effects of R&D expenditures on productivity. Overall, evidence and intuition suggest the benefits of research investment are initially small, then rise to a peak, and finally diminish as the innovation becomes obsolete. This structure has been characterized as an inverted U- or inverted V-shaped distribution. The main problem with directly estimating an unconstrained lag structure is that the number of lagged years that can be included is limited by data constraints. Econometric models introduce many independent variables in a data set that extends only 40 or 50 years. The usual approach is to assume that the weights for the lagged years follow a polynomial of a given degree, thus limiting the number of parameters that must be estimated. Constraining the lag structure in this way can introduce bias. Upward bias may be introduced if the polynomial structure overestimates returns in early years. Errors in early years have relatively larger effects on estimated rate of returns than errors in later years, due to discounting.

Alston and Pardey (1996) provide some simulated results that show how variations in the lag between when research is conducted and when benefits accrue can affect the rate of return. In their simulations they control the benefit stream to assure that cumulative benefits are the same across simulations and that benefits always cease after 30 years. The difference among the simulations is that some benefit streams start earlier at a lower rate, while others start later at a higher rate. As a base of comparison, consider their benefit profile that begins 4 years after research was conducted and generates a rate of return of 46 percent. If the benefit stream is delayed by 2 additional years beginning in year 6, the rate of return falls by 10 percentage points to 36 percent. If the benefit stream is delayed 6 years beginning in year 10, the rate of return falls by 20 percentage points to 26 percent. With a limited time series of data it is difficult to judge whether current approaches under- or overestimate returns. We take a conservative approach and adjust our estimates of the rate of return downward by 10 percentage points because many products may not become commercially available for 6 to 8 years after the bulk of research dollars are spent. It is also likely that the lag is longer for basic research than for applied research or extension.

Spillovers

The productivity of the agricultural sector depends on both public agricultural R&D and private agricultural R&D. Private R&D has accounted for more than half of agricultural research expenditures. Studies of the social rate of return to public research may inappropriately include some spillover productivity gains due to private spending. This is a potential problem in both the economic surplus and production function approaches. Until recently, data on private R&D have not been available. Failure to include private expenditures in statistically estimated relationships leads to overestimates of returns to public research to the extent that public and private R&D spending is positively correlated.

Huffman and Evenson (1989) estimated private research by using the number of patents in agricultural technology fields. Other studies assume that private research expenditures are equal to public research expenditures. See for example Griliches (1964, p. 968), Bredahl and Peterson (1976, p. 688), and White and Havlicek (1982, p. 52). Yee's (1992) estimates of the rates of return to public and private agricultural research explicitly take into account private agricultural research expenditures. He estimates that the social rate of return to U.S. public R&D expenditures falls to 49 percent from 58 percent (after correcting for the omission of private spending).

An incidental result to Yee's (1992) attempt to control for private research expenditures is that he estimated a rate of return to private research of 38 percent. This is very similar to Huffman and Evenson's (1989) estimate of 40 percent rate of return to private agricultural research. Much of the private research in agriculture is conducted by input-producing industries (seeds, chemicals, and farm machinery). Furthermore, Yee's estimates are based on the productive efficiency of the farm sector. Therefore, the 38-percent return reflects mainly those returns not privately captured in the input-producing industries; that is, his estimate reflects returns to this research that has spilled over to farm producers and consumers. The full social return to private research would be higher than 38 percent, as the social return would also include the profits these firms obtain through exercise of their intellectual property rights to obtain monopoly rents. If firms appropriate about half of the returns to their research as suggested for industrial firms overall then the full social return to private research could be nearly 80 percent (Mansfield and others, 1977). Otherwise, if firms are assumed to apply a hurdle rate to research investments of about 20 percent, then the social return to private research may be roughly 58 percent. Both estimates fail to consider the potentially substantial spillovers from research among input-industry firms, namely the ability of one chemical company to build on the research results and findings of another chemical company.

This evidence may also suggest that the private sector has more difficulty in appropriating the returns from agricultural compared with manufacturing industries. Mansfield and others (1977) found that the social rate of return to private research in manufacturing industries to be 50 percent, and the private return to be 25 percent. Yee's estimates suggest a larger share of benefits from private agricultural research spillovers to other firms, farmers, or consumers, compared with Mansfield's estimates for manufacturing. An implication of this hypothesis is that the private sector is more likely to underfund agricultural research than other industries because of the difficulty of appropriating the returns. This evidence is partial justification for the greater involvement of the public sector in agricultural research than in other areas of the economy.

Public and private R&D funding levels are not necessarily independent, as represented in Yee's (1992) study. Possible interrelationships may be positive or negative. Public R&D expenditures may stimulate private R&D expenditures by increasing the technological opportunities from which private firms develop profitable commercial products. Alternatively, public R&D may crowd out private R&D expenditures by acting as a substitute for private R&D. The empirical work of Pray, Neumeyer, and Upadhyaya (1988) finds that public investment in research increases the amount of private investment in research. Thus, a $1 increase in public research results in more than a $1 increase in total research. Public research in basic and pre-technology research increases technological opportunities for applied private research and development. Thus, public research promotes private research by increasing the competitive pressure in an industry. Companies that fail to invest in new technology risk being left behind by their competitors. To the extent that public R&D stimulates private R&D in this way, the returns to public R&D would be underestimated.

Geographical spillovers are particularly important in estimating returns to smaller geographical units, such as individual States. White and Havlicek (1979) found that failure to take into account the geographical spillovers from U.S. regional agricultural research inflated the estimated rate of return to research and extension in the Southern region by more than 25 percent. Evenson (1989) reported substantial spillovers of research benefits between States, with larger spillovers for livestock than for crops. This may explain higher returns to livestock than crop research as found by Bredahl and Peterson (1976) and Norton (1981). States are likely to be most interested in funding research where the benefits accrue to farmers in the State and thus may be more likely to fund crop research. This would drive down the marginal rate of return to crop research. Because the benefits of livestock research spill over widely, State funding for it may be comparably lower. This would drive up the marginal rate of return to livestock research.

U.S. agricultural productivity may similarly benefit from spillovers of technology developed by foreign R&D expenditures. Thirtle and others (1994) incorporate spillovers between the EC countries and from the United States in examining the returns to agricultural R&D for the EC countries. They find that spillovers between European research systems and from the United States may be more important than the direct effects of the national agricultural research systems. The authors conclude that failure to take into account spillovers may bias upward the rate of return to R&D in EC countries. These estimates suggest that an individual country could reduce some spending money on research and take advantage of the research of other countries. This result shows that the public good nature of research is not contained by national borders. If countries act purely in their own self interest, it could lead to global underfunding of agricultural research.

Tax Collection and Deadweight Losses

The economic inefficiencies created by tax collection, termed "deadweight losses" by economists, increase the economic cost of publicly conducted research. For example, a tax on wages reduces labor supplied, and a tax on capital reduces capital investment. Deadweight losses refer to the value of foregone production resulting from imposition of taxes in an economy. Fox (1985) mentions this possibility, which seems to have gone unnoticed previously in the agricultural research literature. Ballard, Shoven, and Whalley (1985) estimated 17-56 cents of deadweight loss per dollar of tax collected in the United States. More recent work aimed at reconciling major differences in the literature concluded that deadweight losses fall between 7 and 25 cents per tax dollar (Ballard and Fullerton, 1992).

Appendix table 1 extends the work of Yee (1992) to incorporate the deadweight loss of taxation for a range of deadweight loss estimates. Extra tax collection costs reduce the effective rate of return on a dollar of public expenditure from 49 percent to between 40 and 46 percent given a range of deadweight loss estimates. Fox (1985) showed a much higher penalty but assumed that the benefits of research are constant through time. The reason Yee's estimates show a smaller penalty is that he directly estimates a lag structure of benefits. The lag structure is crucial to estimating the deadweight loss penalty. To illustrate this, consider three cases: (1) a one-time return occurs in year 1; (2) returns flow at a constant rate indefinitely into the future; and (3) returns start out low and grow at a constant rate over time. In each case, assume that \$1 is invested and earns a 50-percent return before being adjusted for deadweight loss of \$0.30 per dollar. In the first case, $r = [B/C(1+\tau)] - 1$ where τ is the deadweight loss. The rate of return is 50 percent with no deadweight loss if B = \$1.50. The rate of return falls to 15 percent if the deadweight loss is 0.30. In the second case, $r = B/[C(1+\tau)]$. Assuming no deadweight loss, the rate of return is 50 percent if B is \$0.50 but falls to 38 percent if the deadweight loss is 0.30. Finally, in the case where returns begin at a low rate and grow constantly over time, $r = [B/C(1+\tau)] + g$ where g is the growth rate. The rate of return is 50 percent if there is no deadweight loss and B starts at 0.20 and grows at 30 percent per year. With a deadweight loss of 0.30, the adjusted rate of return falls only to 45 percent. As these examples illustrate, the deadweight loss adjustment is very large if returns are heavily weighted to the near term but much smaller if the returns are more heavily weighted to the future.

Appendix table 1—Adjusting the social rate of return to public research for deadweight losses and spillovers from private R&D

Social rates of return	Annual return
	Percent
Estimated without private R&D	58
Estimated with private R&D	49
Estimated with deadweight losses of:	
17 cents/dollar	46
30 cents/dollar	43
56 cents/dollar	40

Source: Data compiled by Economic Research Service. Public rates of return with and without private R&D are from Yee (1992). Rates adjusted for deadweight loss include private R&D. They were calculated from equation 1 in the text by adding the additional deadweight losses to the cost of public research, C_t, and then solving for r. The specific lag structure of returns was that estimated by Yee (1992).

The relatively small deadweight loss penalties based on the Yee (1992) study are due to a pattern of benefits that is very low in initial years but grows rapidly. In contrast, Fox (1985) adjusted the rate of return from 37 percent to 26 percent for a deadweight loss of \$0.30 per dollar of tax collected. Critical to the Fox estimate is that he assumes a constant flow of benefits over time that begins in year zero. If benefits are more realistically assumed to begin 1 or 2 years after the research investment, the adjusted rate of return is 28 percent (1-year delay) and 30 percent (2-year delay).

This feature of the deadweight loss adjustment would likely affect the size of the adjustment among research components, such as basic research, applied research, and extension. The benefits of extension would likely be weighted more heavily toward the near-term, and extension advice may become obsolete relatively quickly as the available technology set, commodity and input prices, and other factors change. Thus, the deadweight loss adjustment for extension would likely be larger. In contrast, the benefits to basic research likely begin relatively small and may grow over time as applications of the basic research result are refined and broadened. Thus, the adjustment for basic research would likely be smaller.

Commodity Programs and Agricultural Surpluses

Government intervention in farm commodity markets is widespread and diverse. Taken at face value, the Federal Government programs that generate surplus stocks and remove acreage from production may be in serious conflict with funding of research and development to increase yields. Alston and Pardey (1996) show, however, that even in cases of surplus production, research that reduces the cost of production can still be beneficial to the economy because production occurs at lower cost and using fewer inputs. Surpluses and budget outlays due to commodity program interventions affect how the benefits of research are distributed between farmers, taxpayers, and consumers but have less effect on the overall net benefit of research.

Farm programs may also distort the incentives to develop and adopt new technology (Alston, Edwards, and Freebairn, 1988). Offutt and Shoemaker (1990) estimated that various farm programs that have removed land from production have encouraged land-saving and manufactured input-using (chemicals, seeds, etc.) technical change in the United States. Thus, there is empirical evidence that commodity programs affect the types of technologies developed and adopted.

Several studies have considered the economic effects of government interventions in commodity markets on the benefits from research (Oehmke, 1988; Alston, Edwards, and Freebairn, 1988; Murphy, Furtan, and Schmitz, 1993; Chambers and Lopez, 1993; Alston and Pardey, 1996). Oehmke (1988) specifically explores how one might adjust the rate of return to research to reflect government interventions. Under his approach he finds that the adjustments can be large enough to make substantial positive rates of return negative. His approach is extreme and likely flawed but raises several questions. In particular, how and whether to account for farm programs in rate-of-return studies depends on some political economy issues that are not easily resolved through appeal to standard economic methodologies.

Most of the economic analyses of farm programs and rates of return to research implicitly make gross and unrealistic assumptions about the political economy of farm programs. There is a standard political economy story behind these analyses: the parameters of the programs are set in the naive belief that productive efficiency will not improve despite decades of evidence to the contrary. Furthermore, when productive efficiency does improve, farm program parameters remain indefinitely unchanged. The result is a significant incentive for farmers to expand production (because costs have fallen compared with commodity target prices). With prices fixed by the program, demand does not increase and the government is faced with ever-accumulating surplus stocks. Further, some analyses assume these stocks are essentially thrown away and thus all government expenditures on farm programs are a pure economic loss. A final important consideration is that many analyses assume that increases in production in the country where the research is conducted affect the world commodity prices. The assumptions used to adjust research benefits for the presence of commodity programs are both unrealistic and extreme.

Explicitly reconsidering the political economy of farm programs might lead to a more realistic scenario as follows: farm programs serve to redistribute income to farmers, particularly in periods of declining prices. An auxiliary effect is that surplus stocks of commodities are used for school lunch programs, distributed to the poor both domestically and abroad through international food aid assistance, or are simply put back in the market during periods of shortages. Farm programs are designed to give considerable flexibility to the Secretary of Agriculture (Secretary) to set target prices, loan rates, and percentage of cropland set aside through the Acreage Reduction Program. By reviewing these program variables yearly, the Secretary exercises control over budget outlays and surplus stock accumulations within the limits of the program's broad dimensions. These various government interventions create distortions as do all government interventions aimed at affecting income distribution. Given the many considerations that go into any political decision, Congress and the Administration have implicitly negotiated what they believe to be a fair amount of redistribution among consumers of different income levels, farmers, and taxpayers. The Secretary's job is to manage program variables to keep budget outlays and other program dimensions in line with the political consensus.

Two factors can result in changes in the rules governing farm programs when they are rewritten: changing views of the appropriate size of outlays and amount of fair redistribution, and changes by the Secretary to manage the program along the wishes of elected officials. In this view of the political economy of farm programs, certain changing conditions are anticipated, specifically: weather, the general economy, export demand and import supply, and productive efficiency arising from technical improvements. Since the specific nature of the changes cannot be predicted ahead of time, flexibility is built into the system to adjust to these changes as they occur. Among these various factors, improvements in productive efficiency are probably the most constant over time. If it were the only factor that was changing, the Secretary could easily adjust program dimensions to avoid unwanted surplus stocks and excessive program outlays. As Alston and Pardey (1996) conclude, if there are pre-existing distortions, the social benefits of research are affected only if R&D worsens the pre-existing distortion. Under this more realistic farm policy scenario, there is little or no reason to expect that improvements in productive efficiency would generate unwanted changes in surpluses or budget outlays. Thus, there is little reason to expect that whatever distortions caused by the programs were worsened or improved by technical change.

In fact, if the above scenario is at all accurate, using the farm program-adjusted rate of return to guide the level or allocation of research would put research spending at odds with the implicit goals of farm programs. Put another way, changing research spending to avoid commodity surpluses or program outlays would be an attempt to reform farm programs through research policy. Such an approach would be neither effective nor economically efficient, since farm programs could respond far faster to meet political goals than could research spending because of the long lead times between funding and technology adoption. The result of such an attempt would seriously misallocate and underfund research spending without having any effect on commodity program budget outlays or surplus stocks.

In summary, research likely has small or negligible effects on the preexisting economic distortions caused by farm programs. Viewing farm programs as largely redistributing the gains from technology is more accurate. A more realistic consideration of farm programs leads to the conclusion that adjusting the rates of return to research for commodity program inefficiencies may lead to misguided decisions on research funding and allocation.

Environmental and Health Effects

The net environmental and health effects of new technology may be negative or positive. Without quantification of these effects, concluding whether estimated rates of return are too high or too low is not possible. For example, the introduction of new agricultural fertilizers and pesticides, largely developed by the private sector, and their increased use, has led to a number of environmental and health concerns. However, yield improvements and reduced crop losses from pests likely reduced the demand for land and consequently its price and the incentive to convert land to cropland. The Conservation Reserve Program, which aims to remove highly erodible land from production, would have had to offer higher rental rates to compete in land rental markets, thus increasing the cost of conservation. Thus, the social rate-of-return adjustment to private sector investments in agricultural chemicals depends on two valuations: (1) the health and environment effects of more chemicals in the environment versus (2) less extensive land use and the lower conservation program costs. The rate of return could be positive or negative. Reilly and Phipps (1988) identify the complexity of linkages between technology and the environment. They note that when taken together, generalizations are not very meaningful because some types of technological advances are benign while others are environmentally damaging. Capalbo and Antle (1989) point out that very little effort has been directed at the measurement of social costs caused by environmental damage and human health risk. They advocate a cross-disciplinary effort and outline a framework for cross-disciplinary research for the measurement and valuation of pollution externalities. Public interest in environmental effects of agriculture and new laws regulating these effects have created significant incentives for public and private researchers to seek environment-saving technology.

Adjustments to social rates of return to research for environmental, health, and safety effects would provide a better accounting of past returns. However, the conclusions to be drawn for future research funding and allocations from adjusted historical rates of return are unclear. The implications of adjusting historical rates of return are unclear because, over time, whether and how environmental effects are regulated have changed. Agricultural chemical research, while principally funded by the private sector, provides a useful illustration of the problems in adjusting historical rates of return for environmental considerations. When many early agricultural chemicals were first introduced, only their immediate health effects were considered. Long-term health effects (for example, carcinogenicity) and broader environmental effects were unknown and, thus, not regulated. In retrospect, one could evaluate the environmental costs of these chemicals and adjust the social rates of return to these private investments downward. New technologies must, however, face a process of product approval and use regulation reflecting what we now know about the potential for broader environmental and health effects. Much of the current private research on agricultural chemicals is aimed at finding new chemicals that are less environmentally damaging and pose fewer health risks. Other private-sector research and much public research is aimed at other approaches for pest control, such as the development of biopesticides and pest-resistant crops.

Consider the implications of adjusting downward the past rate of return to chemical research. The implication would be to reallocate research away from chemical research toward other types of research. Nevertheless, such a reallocation could mean that progress on developing new chemicals that were less environmentally damaging was slowed. In other words, an adjustment in the rate of return meant to speed improvements in the environment could actually have the opposite effect. Such a perverse result could occur because the rate of return on research that occurred 15 or more years ago is only a rough indicator for today's research decisions. For environmental effects, by the time we become aware of the unexpected environmental cost of past research such that we could adjust rates of return, society is likely to have already taken steps to ensure that these environmental costs are reflected in product approval and use regulations.[18] Technologies being developed today may have environmental costs that we do not currently foresee. Because we cannot foresee them, we cannot adjust for them. We do not know whether those areas of research that created environmentally harmful technologies in the past will also be the source of future environmental problems.

An induced-innovation model can be broadened so that applied research responds to the price and regulatory signals provided by the economy and society. If this model uses a public focus assuring that the price and regulatory signals correctly reflect society's valuation of environmental problems, this model represents a more effective and decentralized approach for assuring that research is consistent with environmental goals. This is better than attempting to direct a top-down reallocation based on historic rate-of-return estimates. Competition and the need to introduce marketable products that allow farmers to produce efficiently while meeting environmental requirements provides the incentives for private firms to direct research toward environmental problems reflected in environmental regulation. How the public sector responds to market and regulatory signals is less clear because public research is not directly driven by competitive market forces.

Dislocation and Adjustment Costs

The fact that the introduction of new technology causes dislocation and adjustment has been recognized since some earliest economic thinking on technical change. Schumpeter (1947) used the term "creative destruction" to describe technical change. Economic efficiency is enforced through competition. These incentives operate to reward successful innovators and to penalize less effective innovators (or those who are slow to adopt successful innovations). While the cause of economic efficiency is served by this process and members of society are on average better off, focusing only on the average outcome conceals a range that includes both winners and losers from technological change.

Most concerns regarding dislocation and adjustment have focused on the possibility of job losses resulting from innovations. Smaller and poorer farmers who are slow to adopt new technologies may also face economic losses because of innovation leading to declines in market prices. Schmitz and Seckler (1970) is a rare study that attempted to include the social costs of displaced farmworkers when calculating the rate of return. This study looked historically at the mechanical tomato harvester because of the concern that its introduction had significantly reduced the need for migrant laborers. The largest case in point is the huge rural-to-urban migration that has taken place in the United States and in other industrialized countries. Whether labor-saving technology forced people from the farm or whether they were drawn from the farm by the expectation of higher wages remains an unsettled topic. However, studying the effect of prices and technology on U.S. farm size between 1930 and 1970, Kislev and Peterson (1982) found that the rise in the ratio of nonfarm wages to farm machinery costs could explain statistically nearly all of the growth in average farm size during this period. They concluded that the adoption of large-scale farm machinery was largely in response to, rather than the cause of, the declining number of workers in U.S. agriculture. Workers left agriculture because nonfarm jobs offered better opportunities.

Attempts to limit innovation may eventually force an industry to undergo an even larger adjustment. The U.S. automobile manufacturing sector was able to maintain high wages and employment for many years but ultimately was then forced to adjust in response to foreign competition. Efforts to subsidize directly or provide adjustment assistance to those hurt by new technology can easily become an incentive to avoid adjustment rather than transitory assistance to make an adjustment. Concerns about the distributive effects of new technology may be better served through maintenance of a broad social safety net rather than specific adjustment assistance and damage compensations. In this way, human costs of adjustment can be limited while reducing the disincentives to improve the productive efficiency of the economy.

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[18] There is a long lag between when the health and environmental effects are recognized and when their effects are finally controlled. Even after it is partially controlled, uncertainty in evidence complicates assessing whether the level of control fully internalizes negative effects into private decisions about research. Uncertainty further complicates determining whether regulations under- or overcontrol product development and use. The example in the text is meant to be illustrative.

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