Chapter 22

THE ECONOMICS OF INNOVATION AND TECHNICAL CHANGE IN AGRICULTURE

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Abstract

Innovation in agriculture differs from innovation elsewhere in the economy in several important ways. In this chapter we highlight differences arising from (a) the atomistic nature of agricultural production, (b) the spatial specificity of agricultural technologies and the implications for spatial spillovers and the demand for adaptive research, and (c) the role of coevolving pests and diseases and changing weather and climate giving rise to demands for maintenance research, and other innovations that reduce the susceptibility of agricultural production to these uncontrolled factors. These features of agriculture mean that the nature and extent of market failures in the provision of agricultural research and innovation differ from their counterparts in other parts of the economy. Consequently, different government policies are implied, including different types of intellectual property protection and different roles of the government in funding and performing research. Informal innovation and technical discovery processes characterized agriculture from its beginnings some 10,000 years ago, providing a foundation for the organized science and innovation activities that have become increasingly important over the past century or two. This chapter reviews innovation and technical change in agriculture in this more-recent period, paying attention to research institutions, investments, and intellectual property. Special attention is given to issues of R&D attribution, the nature and length of the lags between research spending and its impacts on productivity, and various dimensions of innovation outcomes, including rates of return to agricultural research and the distribution of benefits.

Keywords

agriculture, factor bias, innovation, intellectual property, market failures, productivity, research lags, spillovers

JEL classification: Q16, O31, O33, O34, O38

1. Introduction

Innovation in agriculture has a long history. It has many features in common with innovation more generally, but also some important differences. These differences and its comparatively long history make agricultural innovation worthy of separate study; albeit with potential lessons for the broader subject of which it is an element.[1]

In many ways the study of innovation is a study of market failure and the individual and collective actions taken to deal with it. Like other parts of the economy, agriculture is characterized by market failures associated with incomplete property rights over inventions. The atomistic structure of much of agriculture that has continued unto the present day means that the attenuation of incentives to innovate is more pronounced than in other industries that have become much more concentrated in their industrial structure.[2] On the other hand, unlike most innovations in manufacturing, food processing, or transportation, agricultural technology has a degree of site specificity because of the biological nature of agricultural production, in which appropriate technologies vary with changes in climate, soil types, topography, latitude, altitude, and distance from markets.

Agricultural production also takes up a lot of space—indeed, about 40% of the world's land area is occupied by agriculture—and the nature of the space varies in ways that are relevant for the choice of technology and the returns to innovation which, as mentioned, are often very site specific. This site-specificity circumscribes the potential for knowledge spillovers and the associated market failures that are exacerbated by the small-scale, competitive, atomistic industrial structure of agriculture.

The biological nature of agricultural production means that production processes take time after resources are committed, during which outcomes are susceptible to the influence of uncontrolled factors such as weather and pests. The agricultural productivity consequences of pests and weather vary in ways that are often difficult or costly to control or predict, not only within a season but also systematically over time and space. Climate change implies a demand for innovation. The coevolution and adaptation of pests and diseases means maintenance research is required to prevent yields from declining. Industrial technologies generally are not susceptible to the types of random shocks or endogenous technological obsolescence that typify agriculture.[3] These features of agriculture give rise to a demand for innovations that reduce the susceptibility of production to uncontrolled factors and allow technology to adapt to sustain production possibilities as pests and diseases, and other aspects of the environment coevolve.

A big part of the longer history of agricultural innovation has to do with the human-induced spatial movement of plants and animals. Most agricultural production today uses genetic material that had its fundamental source hundreds or even thousands of miles away, but this is a comparatively recent phenomenon. After thousands of years of slow development, slow improvement, and gradual movement

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[1] Griliches observed that "Current work on the role of public and private research in productivity growth has deep roots in the early work of agricultural economics. The first micro-production function estimates (Tintner, 1944), the first detailed total-factor productivity (TFP) calculations (Barton and Cooper, 1948), the first estimates of returns to public research and development (R&D) expenditures (Griliches, 1958; Schultz, 1953), and the first production function estimates with an added R&D variable (Griliches, 1964) all originated in agricultural economics (2001, p. 23)."

[2] While the primary agricultural production sector is atomistic in structure, the agribusiness (input supply and food processing) sectors are structured more like the rest of the economy.

[3] Some human-health research, especially research related to disease prevention or mitigation, has these same features.

of plants and animals, all driven by human action, the rate of change accelerated in the past 500 years. An important event in this history was the "Colombian Exchange" that was initiated when Columbus first made contact with native Americans in the "New World" (Crosby, 1987; Diamond, 1999). Most of the commercial agriculture in the United States today is based on crop and livestock species introduced from Europe and Asia (e.g., wheat, barley, rice, soybeans, grapes, apples, citrus, cattle, sheep, hogs, and chickens), though with significant involvement of American species (e.g., maize, peppers, potatoes, tobacco, tomatoes, and turkeys) that are now also distributed throughout the rest of the world. The global diffusion of agriculturally significant plants and animals, and their accompanying pests and diseases, has been a pivotal element in the agricultural innovation story.

Agriculture has one more set of relevant features. It is practiced in every country; every person in the world is a consumer of its products and therefore is affected by innovations in agriculture; and for many of the world's people agricultural innovation is crucial to their existence.[4] Of the 6.4 billion people living in 2005, some 1.4 billion were very poor (earning less than $1.25 per day in 2005 prices) and many of these were subsistence farmers (Chen and Ravallion, 2008; World Bank, 2007). In many countries, especially the world's poorest countries, farmers represent a large fraction of the population, and farming represents a large share of national economic activity, but individual farms are very small enterprises. At the same time in the world's richest countries, like the United States, agriculture represents only a tiny fraction of the national economic activity; less than 1% of the population is involved in farming, and US farms tend to be comparatively large-scale enterprises (with assets of several million dollars) though still economically small relative to typical modern industrial firms.[5] This enormous international heterogeneity of types of farms and farmers implies some differences in demands for farming technologies and innovations.

US agricultural innovation is influenced by and has influenced agricultural innovation in the rest of the world. As with science more generally, the United States has produced a disproportionate amount of the world's agricultural science. While we focus on US agriculture in the twentieth century, we also pay attention to agricultural innovation in other countries and at other times. Agricultural innovation began with the invention of agriculture itself. To provide some longer-term and broader context for our review of the economics of innovation in US agriculture in the twentieth century, we begin with a brief history of agricultural change.

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[4] In 2000, agriculture (including forestry and fishing) represented 24% of total GDP (gross domestic product) on average in countries with per capita incomes less the $765 (the World Bank 2003 threshold designating low-income countries). About 2.6 billion people depend on agriculture for their livelihoods, either as actively engaged workers or as dependents (FAOSTAT, 2004). In 2000, just over half (52%) of the world's population were living in rural areas and, of these, about 2.5 billion people were estimated to be living in agriculturally based households (World Bank, 2003). The global agricultural labor force includes approximately 1.3 billion people, about a fourth (22%) of the world's population and half (46%) of the total labor force (Deen, 2000).

[5] In 1900, 17.5% of the US farm acreage was on holdings less than 100 acres in size; by 2002 the corresponding share was just 4.3% (Alston et al., 2010). At the other end of the spectrum, the share of acreage in large farms (i.e., farms of 1000 acres or more) grew from nearly one-quarter (just under 24%) of the total in 1900 to more than two-thirds (nearly 67%) of the total in 2002. More-recent times have witnessed relatively rapid growth in agricultural output from larger operations with sales of at least $0.5 million per farm per year (in 2003 prices). They accounted for 45% of the US agricultural output in 2003, up from 32% in 1989 (MacDonald et al., 2006). Correspondingly, the share of production coming from smaller farms ($10,000–$250,000 per farm per year in sales) fell from 40% to 26%.

2. Informal innovation and technology discovery

The invention of agriculture around 10,000 years ago heralded a shift from nomadic hunting and gathering to more managed forms of food, feed, and fiber production. The domestication of crops initially involved saving seed from one season for planting in subsequent years. Later, farmers purposefully selected crop varieties and so in practice began matching and, by repeated selection over many years, adapting crop genetics to the environment in which the crop was grown. From its inception, enhancing $G \times E$ (i.e., gene by environment) interactions was an intrinsic feature of agriculture.

However, just as the G-part of agriculture changed over time because of human activity, so too did the E-element. Farmers first began altering their local environments by clearing and leveling fields, weeding, and engaging in various forms of irrigation. Then, as people began to migrate they carried their crops with them, found new ones along the way, and, eventually, sent expeditions abroad scouring the world for new cropping material. Viewed from this historical perspective, the geographical footprint of agriculture has been ever-changing; even more so when looking at the spatial extent of particular crops that get moved around both among and within countries.

Scientifically bred crop varieties (and livestock breeds) and their associated agricultural management practices have a history of barely 100 years. In the middle of the nineteenth century and especially at the beginning of the twentieth century, a number of important things changed. Specifically, Darwin's theory of evolution, the pure-line theory of Johannson, the mutation theory of de Vries, and the "discovery" of Mendel's laws of heredity all contributed to the rise of plant breeding in the beginning of the twentieth century.[6] The mid-nineteenth century work of organic chemists like von Leibig led to substantial improvements in our understanding of the role soil fertility plays in plant growth.[7] Pasteur's germ theory of disease, together with other fundamental insights gained from bacteriology, virology, and related microbiological sciences, spurred the development of animal vaccines and more broadly promoted the development of methods to manage and mitigate production losses associated with crop and livestock diseases. Along with genetic innovations, this growing body of scientific knowledge fostered a host of other innovations in pest and disease management, animal husbandry, and the like, which accompanied "labor-saving" innovations that augmented and replaced human labor with wind and water mills, and livestock draft power, eventually to be replaced with tractors and other machines.

Like the other types of innovations in agriculture and elsewhere, for most of human history mechanical innovations and genetic improvements were the result of tinkering and informal experimentation by individuals, with findings communicated informally by word of mouth, if at all. Organized research is itself a relatively recent innovation, and has been an element of public policy for less than

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[6] In 1900, the Dutch botanist Hugo de Vries, the German botanist Correns, and the Austrian agronomist Tschermark independently and about the same time published studies on the laws of heredity that had been anticipated in the 1866 paper by the Austrian monk Gregor Mendel. When Mendel's paper was published in the *Proceedings of the Natural History Society of Brünn*, it had little impact, and was cited very few times over the subsequent 35 years.

[7] Von Liebig's book *Organic Chemistry in Its Application to Agriculture and Physiology* published in 1840 in both Germany and Great Britain triggered widespread interest in the application of science to agriculture. Within 8 years of its publication, von Liebig's book had gone through 17 different editions, translations and revisions, mostly in Germany, England, France, and the United States, but also in Denmark, Italy, the Netherlands, Poland, and Russia (Rossiter, 1975; Russell, 1966; Salmon and Hanson, 1964). Like others, Ruttan (1982) viewed von Liebig's book as the critical dividing line in the evolution of modern agricultural science.

200 years (Ruttan and Pray, 1987). Similarly, intellectual property rights (IPR) have existed in some form for centuries, but effective patents and patent-like rights have been formalized only relatively recently in most countries (e.g., in 1790 in the United States). Extending the scope of intellectual property (IP) protection to include the biological innovations used in agriculture is an even more-recent phenomenon.

Consequently, many innovative achievements went unrecorded and are not associated with any particular individual or particular research investment. But some landmarks in agricultural history associated with scientific discoveries, innovations, and policies related to innovation have been recorded, and archeologists, paleontologists, and other historical researchers have uncovered some of the longer history of agricultural innovation.

Home-grown technologies represent one source of growth in agriculture. Tapping technologies developed in other places—especially in the rich countries where the preponderance of the agricultural R&D has been done—has also been a feature of agricultural progress the world over and can be traced back to the very beginnings of human history.[8] Much of the relocation and transformation of plants and animals to provide food and fiber was done gradually and informally, and not always intentionally. In more-recent times the same kinds of activities have become part of the formal public and private processes of agricultural innovation undertaken deliberately. Governments and private investors have spent considerable resources both to prospect around the world for existing genetic resources to meet particular environmental or economic challenges, and to adapt plants and animals to achieve particular purposes.[9] Institutions have been developed to encourage such investments, not only in genetic resources for agriculture but also in other types of innovations such as mechanical, chemical, and information technologies. Even today, the spatial aspect of the technologies and the potential for international technology spillovers continue to play important roles in circumscribing incentives to invest.

3. Innovation institutions, incentives, and inducements

The amount, orientation, and institutional details of investments in agricultural innovation are shaped by economic incentives and inducements. This section explores these influences on agricultural research and development in a global setting, highlighting US developments. This provides the context for the

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[8] This spatial aspect of the agricultural innovation process, and its relationship with the spatial distribution of endowments of species, climate, and other resources, has played an important role in shaping that history (for instance, see Jared Diamond's *Guns, Germs, and Steel*, and Tim Flannery's *The Eternal Frontier*). Flannery (2001).

[9] Fowler (1994) observed "At a time when smuggling was punishable by death, [Thomas] Jefferson smuggled upland rice sewn into the linings of his coat out of Italy in an attempt to introduce it to and encourage its cultivation in South Carolina (p. 14)." The US government also got directly involved in plant introductions, beginning at least in the early part of the nineteenth century. For example, Ryerson (1933) wrote "On September 6, 1827, at the direct instigation of President John Quincy Adams, another circular was sent to all consuls explaining the importance of plant introduction, directing that seeds and plants be sent to the United States, listing the type of information desired about each, and accompanied the circular with a five-page supplement with complete instructions on how to pack and ship plant material under conditions on board sailing vessels, including protection from salt spray 'especially when the waves have white frothy curls upon them.' The Secretary of the Navy ordered all naval commanders to lend every assistance at any port from which consuls wished to ship plants (pp. 113–114)."

following two sections which consider the private versus public configuration of agricultural R&D as well as the shifting spatial and substantive structure of the research.

3.1. Institutions for investments

In the past half-century, agricultural science achieved a great deal. Since 1961, the world's population has more than doubled, from 3.1 to 6.5 billion in 2006. Over the same period, total production of cereals grew faster than population (from 878 million metric tons in 1961 to over 2,221 million metric tons in 2006), and this increase resulted largely from unprecedented increases in crop yields (FAOSTAT, 2008; Pardey et al., 2007). The fact that the Malthusian nightmare has not been realized over the past 50 years is attributable in large part to improvements in agricultural productivity achieved through technological change enabled by investments in agricultural R&D.

In spite of its remarkable track record of success, countries around the world continue to invest too little in agricultural research—in the sense that the social returns to private and public investments are much greater than the opportunity costs of funds. This chronic underinvestment reflects a combination of a market failure, leading to a private-sector underinvestment from a broader societal perspective, and a government failure, with too little done to correct the problem. The market failures extend beyond national boundaries; the world has collectively invested too little, the global stock of scientific knowledge that fuels productivity growth in agriculture worldwide is too small, and agricultural productivity growth has been too slow—and will continue to be so at least for a time, even if governments take immediate action to eliminate the problem (James et al., 2009).

Prior to the nineteenth century, agricultural research typically was conducted by private individuals, usually innovative farmers or estate or plantation owners.[10] At the beginning of the nineteenth century Great Britain was regarded by those interested in agricultural improvement as the "school for agriculture"; but by the end of the century leadership in the application of science to the problems of agriculture had passed to Germany, and during the latter half of the nineteenth century it was almost obligatory for anyone with a serious interest in agricultural science to study in Germany. The German innovations in the organization of public-sector agricultural research and education provided the model for the organization of the national public-sector agricultural research system in the United States, including the state agricultural experiment stations (SAESs) and the US Department of Agriculture (USDA), established in the latter half of the 1800s. Much of the research and extension leading to agricultural productivity growth in the United States during the twentieth century, particularly crop and animal improvement, was a product of the federal-state agricultural research system.

In most countries, the primary source of funding for public-sector agricultural R&D continues to be general tax revenues, which may be an expensive source of finance (e.g., Fox, 1985). Governments around the world have developed a range of institutions for increasing their national investment in agricultural R&D. Some of these institutions provide mechanisms for enhancing individual incentives to invest, including IPR, tax concessions, fees for service and contract R&D, prize mechanisms, endowment funding (via foundations), and so forth; others enable the development of collective action programs financed by commodity taxes (sometimes called levy-based or check-off schemes).

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[10] For elaboration see Olmstead and Rhode (2000, 2001, 2008) and Ruttan (1982, pp. 65–90).

3.2. Incentives to innovate—Intellectual property

IPR such as patents, trademarks, plant breeders' rights and copyrights are among the more prominent public policy responses intended to stimulate the creation and dissemination of inventions.[11] In recent years, many countries have strengthened their patent systems as part of domestic initiatives to upgrade their national innovation systems (Mowery, 1998), or to comply with international agreements, and specific IP innovations have been developed to apply to plants and animals.

Exclusionary IPR such as patents or plant breeders' rights are costly to obtain and to exercise. Notably, significant shares of agriculture in many developing countries involve subsistence or semisubsistence cropping systems, with limited commercial opportunities to market seed and, consequently, less incentive to seek varietal rights, even if a legal option to do so existed. As a consequence of these features of reality, plant variety rights are still heavily biased to rich-country jurisdictions and heavily biased to higher-valued fruits, vegetables, and ornamentals. The extent of formal IPR pertaining to plants is on the rise in selected developing-country jurisdictions—notably Brazil, China, and India—but the vast majority of crops in the vast majority of developing counties are still subject to little if any effective, legally sanctioned forms of IP protection (see Koo et al., 2004; Louwaars et al., 2005; Srinivasan, 2005).

3.3. Alternatives to intellectual property

The incentive effects of patents have long been recognized, as have the costs of restricting the use of the patented product or process for the duration of the patent monopoly. Mechanisms such as research contracts and prizes may also be effective in generating new innovations in certain circumstances (Wright et al., 2007). While these types of innovation processes avoid monopoly-pricing behavior, and thereby increase consumer benefits, the problem remains of setting the right prize or contract support according to the value of the innovation.[12]

Rather than public goods, many types of agricultural R&D may be better thought of as collective goods, for which the relevant collection of beneficiaries may be a group of producers (and consumers) of a particular commodity coming from a particular region. Economic efficiency (along with some concepts of fairness) is likely to be promoted by funding research using arrangements that mean the costs are borne in proportion to the benefits to the greatest extent possible.[13] Thus, different agricultural R&D programs and projects may call for different funding mechanisms, that reflect the geographic

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[11] The economic effects of plant variety protection in the United States have been studied by Perrin et al. (1983), Butler and Marion (1985), Knudson and Pray (1991), and Alston and Venner (2002). Studies dealing with other countries include Godden (1998) for Australia, CFIA (Canadian Food Inspection Agency (2002) for Canada, Diez (2002) for Spain, and Koo et al. (2006) for China.

[12] More recently, "open source" approaches to developing software products using, for example, *Apache* and *Linux* have attracted much attention as a collaborative approach to innovation development (Benkler, 2004). The Public-Sector Intellectual Property Resource for Agriculture (PIPRA) initiative is an attempt by public and nonprofit researchers to provide mutually consenting parties reciprocal access to their proprietary technologies, while also making such technologies available to developing-country researchers in ways that do not relinquish licensing options and potential royalty revenues from private-sector entities in developed countries (Atkinson et al., 2003; Delmer et al., 2003; Graff et al., 2003).

[13] As discussed by Alston et al. (2003, 2004) and the Productivity Commission (2007), commodity taxes or levies are used extensively in Australia to finance commodity-specific agricultural R&D.

focus and the commodity orientation of the research, with due allowance for the role of economies of size, scale, and scope in research as well as various types of political costs, administrative costs, and transaction costs associated with having different research organizations with overlapping jurisdictions (Alston and Pardey, 1996).

Many types of research exhibit significant economies of size, scale, or scope, so that it makes sense to organize relatively large research institutions; but much agricultural technology is characterized by site specificity, related to agroecological conditions, which defines the size of the relevant market in a way that is much less common in other industrial R&D (Alston and Pardey, 1999).[14] One way to think of this is in terms of the unit costs of making local research results applicable to other locations (say, by adaptive research), which must be added to the local research costs. Such costs grow with the size of the market. Consequently, while economies of size, scale, and scope in research mean that unit costs fall with size of the R&D enterprise, these economies must be traded off against the diseconomies of distance and adapting site-specific results (the costs of "transporting" the research results to economically "more distant" locations). Thus, as the size of the research enterprise increases, unit costs are likely to decline at first (because economies of size are relatively important) but will eventually rise (as the costs of economic distance become ever-more important).

3.4. Inducements to innovate

Public research investments and the provision of IP have mainly influenced the total rate of investment in innovation and technical change, but other government policies have also influenced the direction of change. Whether they are the result of market forces alone, or government policies, movements in relative prices of farm inputs and outputs influence the output orientation and factor bias of technical change.

Modern interest in the effects of changes (and differences) in relative factor endowments and prices on the rate and direction of technical change was initially stimulated by an observation by Hicks (1932) that "The real reason for the predominance of labour saving innovation is surely that . . . a change in relative factors of production is itself a spur to innovation and to innovation of a particular kind—directed at economising on the use of a factor which has become relatively expensive (pp. 124–125)." Hicks' suggestion was neglected until the early 1960s when it was revisited in both empirical and theoretical contributions.

Hayami and Ruttan (1970, 1971) and several colleagues initiated a series of time-series and cross-sectional tests of the induced technical change hypothesis against the experience of technical change in agriculture in both developed and developing countries. Their initial tests were based on the long-term experience of the agricultural sectors of Japan and the United States. The United States and Japan were characterized by large differences in factor endowments and in price ratios among factors of production. Moreover, these differences widened over time. In spite of these differences, Japan, and the United States have, at least until very recently, attained high and sustained rates of growth in agricultural output and productivity. Hayami and Ruttan (1970, 1971) posited that a common basis for rapid growth in agricultural output and productivity was the adaptation of agricultural technology to the sharply

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[14] For a discussion of these scope and scale ideas in the context of agricultural R&D, see Pardey et al. (1991), Byerlee and Traxler (2001), and Jin et al. (2005).

contrasting differences and changes in the factor proportions in the two countries. An important part of this adaptation was the ability to generate a continuous sequence of agricultural innovations biased toward saving the limiting factors. In Japan advances in biological and chemical technology were deemed to play a very important role in advancing land productivity while in the United States advances in mechanical technology were seen to be important in enhancing labor productivity.[15] Hayami and Ruttan (1970, 1971) recognized, of course, that not all mechanical innovations were motivated by labor-saving incentives nor were all biological innovations necessarily motivated by land-saving incentives. In Japan, horse plowing was propagated as a device to cultivate the land more deeply to increase yield per hectare. In the United States varieties of crops such as tomatoes and apples have been developed to facilitate mechanical harvesting. Mechanical innovations can be land-saving and biological innovations can be labor-saving, depending on trends in the conditions of factor supply and factor prices, as well as the scientific or technical constraints involved.

The idea of induced innovation is intuitive, but has been controversial. Predating and paralleling these empirical investigations of the 1970s was a vigorous theoretical debate about the inducement mechanism. Salter (1960) noted that “At competitive equilibrium each factor is being paid its marginal value product; therefore all factors are equally expensive to firms (p. 16).” “[The] entrepreneur is interested in reducing costs in total, not particular costs . . .. When labor costs rise any advance that reduces total cost is welcome, and whether this is achieved by saving labor or saving capital is irrelevant (Salter, 1960, pp. 43–44).” However, this argument is weakened if we think of technologies as being mutually exclusive. A change in the relative prices of different factors (or different products) changes the relative returns to different types of research (leading to different types of output-augmenting or factor-saving innovation), and changes the relative economic advantages from the adoption of different types of mutually exclusive innovations. This mutually exclusive nature of certain types of research investments or adoption decisions means that the path of innovation may well be influenced by relative prices.

The empirical challenges in this area of analysis are large, partly because it is fundamentally difficult to distinguish between conventional factor substitution effects (given the state of technology) and shifts in relative factor use associated with changes in technology; more so when we recognize the inherent dynamics of the issue. Part of the problem rests with using comparative-static approaches to model what is in essence a dynamic process. To address the substitution versus technical change conundrum, Ahmad (1966, 1967) postulated an innovation possibility curve, as the envelope of the set of potential production processes that may arise from a given expenditure on R&D.[16] Binswanger (1974a,b,c) recast this microeconomic formulation of the induced innovation model in a dual framework and developed additional empirical methods for assessing the conformity of empirical data with the notion that changes in relative (factor) prices may influence the factor bias of technical changes.[17] More recently, Olmstead and Rhode (1993, 1998) presented criticisms that related to specific elements of the US empirical evidence presented by Hayami and Ruttan (1970, 1971). Our conclusion is that the

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[15] Subsequently, over the more recent decades, the patterns of technical change in agriculture in the two countries have converged as relative prices between the countries have converged.

[16] Others who weighed in on this debate include Fellner (1961, 1967), Nordhaus (1973), Kennedy (1964, 1967, 1973), and Rosenberg (1969). Binswanger (1978) and Thirtle and Ruttan (1987) provide useful summaries of this history of thought.

[17] More contemporary efforts to test the notion of induced innovation in agriculture include Kawagoe et al. (1986) for Japan, Karagiannis and Furtan (1990, 1993) for Canada, Khatri et al. (1998) for the United Kingdom, and Thirtle et al. (2002) for the United States.

concept of induced innovation is intuitively attractive and fundamentally plausible, and broadly consistent with the main historical facts. However, work remains to be done to deal with the conceptual and empirical challenges that have only been partly addressed to date before much can be said about the importance of induced-innovation responses as an element of technological change in agriculture.

4. Global investments in agricultural research and development

In 2006, an estimated $887.2 billion international dollars in 2000 prices was spent on all the sciences worldwide (Pardey and Dehmer, 2010).[18] This spending represented about 1.7% of global GDP exceeding twice the inflation-adjusted total of $374.2 billion in 1981. High-income countries did most of this research (i.e. 80.6% in 2000); although R&D directed toward agriculture—recognizing that much other research in basic biology, health, (bio-)informatics, and other disciplines, for example, also has relevance for agriculture—constituted only 4% of their total research expenditure in 2000, and just 7.3% of the respective public-sector share.[19] Among developing countries, a large share of the total R&D (41.8% in 2000) was concentrated in just three countries—China, India, and Brazil. These countries accounted for only 25.9% of the developing country total in 1980. Similar to rich-country trends, where agricultural R&D is a declining share of R&D, the average share of public agricultural R&D relative to public science spending in developing countries dropped from 22.5% in 1981 to 15.4% in 2000. However, the intensity of public investment in agricultural R&D of the biggest developing countries—China, India, and Brazil—dropped much more substantially, from 20.3% to 8.6%, pointing to a sustained trend among the more technologically advanced developing economies in the world to invest a greater share of R&D resources in areas other than agriculture.

4.1. Public agricultural research and development spending

Worldwide, public investment in agricultural R&D increased by 35% in inflation-adjusted terms between 1981 and 2000 from an estimated $14.2 to $20.3 billion in 2000 international dollars. It grew faster in less-developed countries, which now account for about half of global public-sector spending—up from an estimated 41% share in 1980.[20] However, developing countries account for about one-third of the world's total agricultural R&D spending when private investments are included.

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[18] This figure includes the total spending by public and private entities across all areas of science (i.e., including agricultural, medical, and engineering R&D, information technology and the social sciences, and so on).

[19] Food and health outcomes are inextricably intertwined through nutrition, but in some important cases the agriculture-human health linkages are even more immediate.

[20] As Pardey et al. (1992) described, these country and regional estimates of spending totals, shares, and rates of change are sensitive to the underlying national spending estimates as well as the procedures used to deflate and convert national spending estimates from the nominal local currency units in which they are typically compiled into the common currency unit reported here, 2000 international dollars. Aside from a revision to the public-sector series for Japan, the series referenced here is the same as those reported in Pardey et al. (2006b) except that the currency conversions used a revised purchasing power parity (PPP) series obtained from Martin (2008) (available on line from the World Bank at http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS/ICPEXT/0,,menuPK:1973757~pagePK:62002243~piPK:62002387~theSitePK:270065,00.html). As a consequence of these revisions, the estimated OECD share of the global agricultural R&D spending total increased from the 44.3% reported in Pardey et al. (2006b) to the 50.6% share reported here.

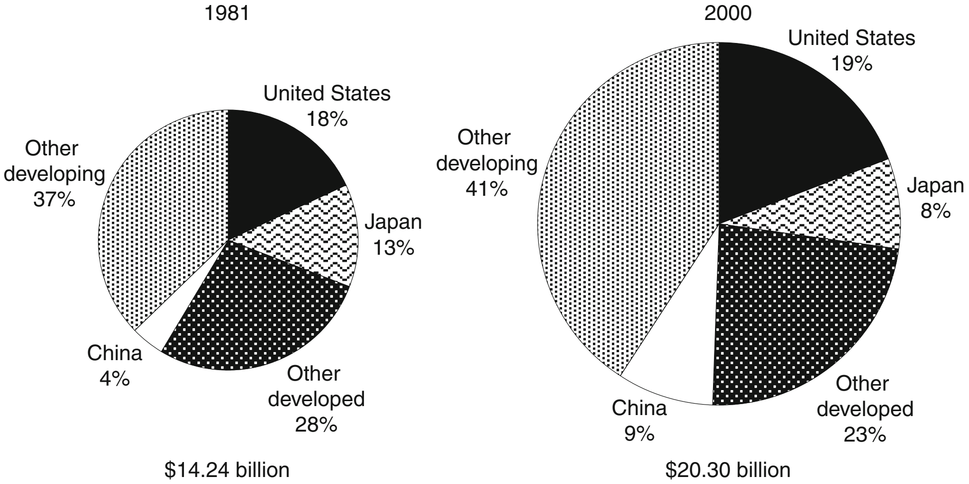

Figure 1. Global public agricultural R&D spending trends, 1981 and 2000. Source: James et al. (2009) based on recalibrated ASTI (Agricultural Science and Technology Indicators) data originally reported in Pardey et al. (2006b). Currency units formed using revised purchasing power parity indexes from the World Bank obtained from Martin (2008). See text footnote 20 for additional details. *Notes*: These estimates exclude Eastern Europe and former Soviet Union countries. To form these regional totals, we scaled up national spending estimates for countries that represented 79% of the reported sub-Saharan African total, 89% of the Asia and Pacific total, 86% of the Latin America and Caribbean total, 57% of the West Asia and North Africa total, and 84% of the high-income total.

Even so, agricultural research intensities (expressing agricultural R&D spending as a percentage of agricultural GDP) in developing countries are static and remain much lower than in the developed countries.[21]

The Asia and Pacific region accounted for an ever-larger share of the developing country spending on public agricultural R&D since 1981 (25.1% of the world total in 2000, up from 15.7% in 1981). In 2000, just two countries from this region, China and India, accounted for 29.1% of all developing country expenditure on public agricultural R&D, a substantial increase from their 15.6% combined share in 1981 (Figure 1). In stark contrast, sub-Saharan Africa continued to lose market share—its share fell from 17.9% of the total investment in public agricultural R&D by developing countries in 1981 to 11.9% in 2000 (Pardey and Dehmer, 2010; Pardey et al., 2006b).[22]

A notable feature of the trends was the contraction in support for public agricultural R&D among developed countries. While spending in the United States increased in the latter half of the 1990s, albeit more slowly than in preceding decades, public agricultural R&D was massively reduced in Japan (and also, to a lesser degree, in several European countries) toward the end of the 1990s, leading to a

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[21] Developed countries as a group spent $2.36 on public agricultural R&D for every $100 of agricultural output in 2000: a sizable increase over the $1.62 spent per $100 of output two decades earlier, but about the same as the 1991 estimate of $2.33. In contrast, developing countries spent just $0.53 on agricultural R&D for every $100 of agricultural output in 2000.

[22] Overall investments in agricultural R&D in sub-Saharan Africa grew by less than 1% per annum during the 1990s, the continuation of a longer-term slowdown (Beintema and Stads, 2004).

reduction in the rate of increase in developed-country spending as a whole for the decade. The more-recent data reinforce these longer-term trends. Namely, support for publicly performed agricultural R&D among developed countries is being scaled back, or slowing down, and R&D agendas have drifted away from productivity gains in food staples toward concerns for the environmental effects of agriculture, food quality, and the medical, energy, and industrial uses of agricultural commodities. Nonetheless, developed countries as a group still account for about one-half of public agricultural R&D worldwide. Given the role of spillovers, a continuation of the recent trends in funding, policy, and markets is likely to have significant effects on the long-term productivity path for food staples in developed and developing countries, alike (Alston et al., 2010; Pardey et al., 2006a).

4.2. Private agricultural R&D investments

The private sector has continued to emphasize inventions that are amenable to various IP protection options such as patents, trade secrets (including those associated with hybrid crops), and more recently, plant breeders' rights and other forms of IP protection. The private sector has a large presence in agricultural R&D, but with dramatic differences among countries.

In 2000, the global total spending on agricultural R&D (including prefarm-, onfarm-, and postfarm-oriented R&D) was an estimated $33.7 billion. Approximately 40% was conducted by private firms and the remaining 60% by public agencies. Notably, 95% of private R&D was performed in developed counties, where 55% of total agricultural R&D was private, a sizeable increase from the 44% private share in 1981. This trend in private R&D spending in developed countries may well continue if the science of agriculture increasingly looks like the sciences more generally. In the United States, for example, the private sector conducted nearly 55% of agricultural R&D in 2000, compared with 72% of all R&D expenditures in that same year (NSF, 2005). These increasing private shares reflect increasing industry R&D by the farm-input supply and the food processing sectors. Around this general trend countries varied in their spending patterns. According to data underlying those reported in Pardey et al. (2006b), Japan had a slightly larger share of its agricultural R&D in the private sector than the United States, whereas Australia and Canada—both more reliant on privately developed, technology-intensive imports of farm machinery, chemicals, and other agricultural inputs, and food processing—had private-sector shares of agricultural R&D spending less than 35% in 2000.

In developing countries, only 6.4% of the agricultural R&D was private, with large disparities in the private share of spending among regions of the developing world. In the Asia and Pacific region, around 9% of the agricultural R&D was private, compared with only 1.7% of the R&D throughout sub-Saharan Africa. South Africa carried out approximately half of the total measured amount of private R&D performed throughout sub-Saharan Africa.

The disparity in the intensity of agricultural research between rich and poor countries, noted above (specifically footnote 21), is magnified dramatically if private research is also factored in (Figure 2). In 2000, total agricultural R&D spending amounted to 0.54% of agricultural GDP for developing countries as a group (i.e., for every $100 of agricultural GDP, just 54 cents was spent on agricultural R&D). In developed countries, the comparable intensity ratio was 5.28%, almost 10 times greater.

This private investment activity is both encouraged by government through the provision of property rights and financial incentives, and hampered by government regulation over the technologies that can

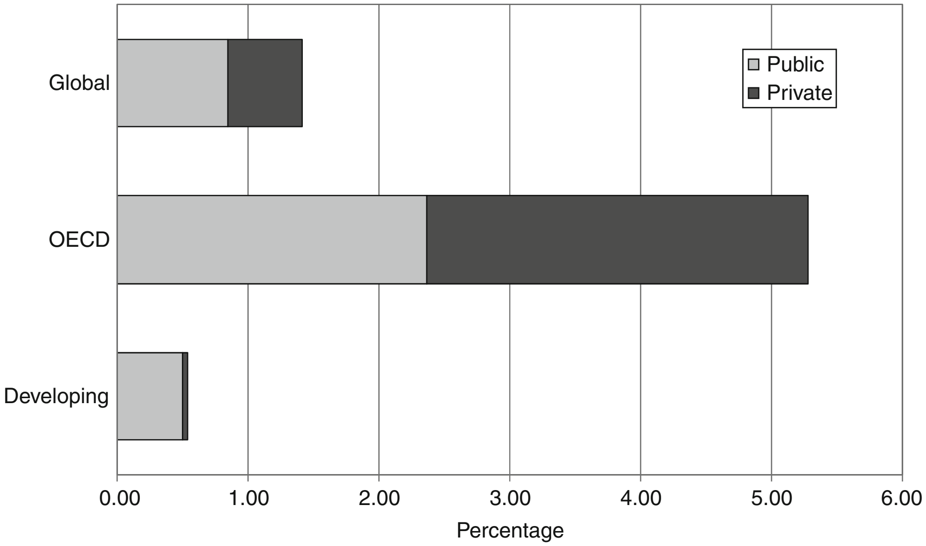

Figure 2. Public, private, and total agricultural R&D intensities, circa 2000. Source: James et al. (2009). *Notes*: These intensity ratios measure total public and private agricultural R&D spending as a percentage of agricultural output (agricultural GDP).

be used in agricultural production and the processes of regulatory approval for new technologies. Every aspect of agricultural production is subject to a host of regulations—designed, at least ostensibly, to protect worker health and safety, food safety, animal welfare, and the environment, and in some cases to protect vested interests. Some of these regulations apply to products and others to the processes used to produce them. For instance, in many countries, including the United States, milk must be pasteurized and it must not exceed maximum tolerances for bacterial contamination to be allowed to be sold for human consumption (see Balagtas et al., 2007); DDT is no longer allowed to be used to manage insect pests and methyl bromide is being phased out; for much of the twentieth century, the California cotton One Variety Law allowed only one variety of cotton (*Acala*) to be planted (Constantine et al., 1994).

Nowadays, in the United States the process of regulatory approval can take 10 years at a cost of $5–$15 million, before a new biotech crop variety can be released for commercial adoption (Kalaitzandonakes et al., 2006); regulatory approval costs are lower but still substantial for new pesticides. These and other regulatory barriers have influenced the rate and path of innovation, with a tendency to favor technologies that apply on a larger scale (e.g., to the main crops), and are thus more likely to justify a large up-front cost of overcoming regulatory hurdles on top of research costs (e.g., Just et al., 2006). Hence, the progressive banning of certain chemical pesticides, and the high fixed cost of regulatory approval for new pesticides or genetically modified, pest-resistant crop varieties, have made technological orphans of many of the minor crops. Other policy-induced biases in the path and pace of innovation may have been induced by the distortions in prices of inputs and outputs caused by farm commodity subsidies (e.g., see Alston et al., 1988; Hayami and Ruttan, 1970; Mellor and Johnston, 1984; Schultz, 1978). Government-induced distortions in incentives for the private sector in the more developed countries have influenced the incentives to invest in innovation and the types of technologies that have been made available to farmers in both rich and poor countries alike.

4.3. International agricultural R&D

In the mid-1940s, programs of internationally conceived and funded agricultural research were launched in an effort to overcome the biases against the development and diffusion of agricultural technologies among developing countries. These efforts evolved into the International Rice Research Institute (IRRI) in the Philippines in 1960 and the International Maize and Wheat Improvement Center (CIMMYT) in Mexico in 1967. The further development of international agricultural research centers took place largely under the auspices of a collective funding instrument known as the Consultative Group on International Agricultural Research (CGIAR, or CG for short), established in 1971 as bilateral and multilateral donors bought into the model. Over the following decades, the CG system grew to include a total of 15 centers spending a total of $450 million in 2006.[23] While the CG system has captured the attention of the international agricultural R&D and aid communities, through the impact of its scientific achievements and through its pivotal role in the Green Revolution, it has spent only a small fraction of the global agricultural R&D investment. In 2000, the CG system represented 1.5% of the $20.3 billion (2000 prices) global public-sector investment in agricultural R&D and just 0.9% of all public and private spending on agricultural R&D.

5. US agricultural research institutions and investments

The history of agricultural R&D in the United States is one of jointly evolving state and federal, public, and private-sector roles.[24] The public-sector role developed mainly over the past 100 years.[25] In 1889, shortly after the Hatch Act was passed, federal and state spending appropriations totaled $1.12 million. Over a century later, in 2006 the public agricultural R&D enterprise had grown to $4.62 billion, an

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[23] See Baum (1986) and Alston et al. (2006) and the references therein for more detail on the history of the CGIAR. Commenting on the changing sources of support for CGIAR activities, Alston et al. (2006, p. 324) note that "In the beginning (using 1972 figures), the private foundations provided 49 percent of the total funding. European nations as a group provided 15 percent; the United States 18 percent; and the World Bank 6 percent. The picture is now very different.. . . [Support from private foundations]. . .has fallen in nominal terms and now constitutes less than 3 percent of the total. In 2004, European nations as a group (including multilateral support through the European Commission) provided $181 million, or 41.4 percent of the total. In the same year the World Bank provided $50 million (11.4 percent), the United States $54.2 million (12.4 percent), and Japan $14.4 million (3 percent of the total)."

[24] The measures of research spending and productivity discussed here and shown in Figure 3 are described and documented in detail by Alston et al. (2010), along with some discussion of the institutions. Kerr (1987), Huffman and Evenson (1993), and Alston and Pardey (1996) provide more details on the institutional history; see also Schultz (1953).

[25] Active intramural USDA research began immediately with the establishment of the USDA in 1862 and the publication of the first research bulletin in that same year describing the sugar content and suitability for winemaking of several grape varieties (Wetherill, 1862). However, although the early years of the USDA were characterized by a slow and steady expansion of the department's internal scientific activities, most of the department's work was devoted to "service" rather than the discovery and development of new knowledge. It was not until the Progressive Era leadership of James "Tama Jim" Wilson, from 1897 to 1913, that the USDA budget grew dramatically (by over 700% during Wilson's tenure), and, by 1904, employment of scientists within the USDA surpassed total employment of scientists in the State Agricultural Experiment Stations (SAESs).

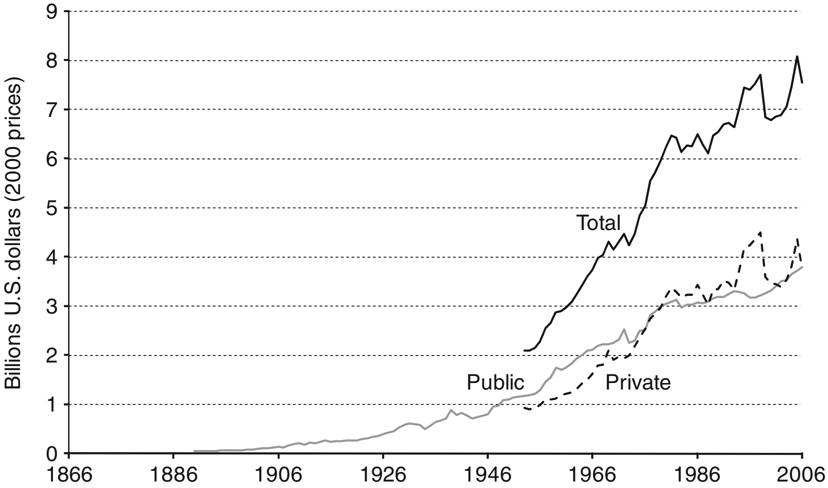

Figure 3. US public, private, and total agricultural R&D expenditure trends, 1890–2006. Source: Alston et al. (2010), Pardey et al. (2010), and Dehmer and Pardey (2010). *Notes*: Nominal research expenditure data were deflated by a US agricultural research price index reported in Pardey et al. (2010). Public series is inclusive of all but the forestry R&D performed by the SAESs and the USDA. The private series is defined as privately performed food and agricultural R&D undertaken in the United States.

annual rate of growth of 7.1% in nominal terms and 3.8% in real (i.e., inflation adjusted) terms (Figure 3).[26] Intramural USDA and SAESs research accounted for roughly equal shares of public research spending until the late 1930s, after which the SAES share grew to 69% of total public spending on agricultural R&D by 2006 (Figure 4). In 1915, the first year in which federal funds were made available for cooperative extension between the USDA and various state extension agencies, almost $1.5 million dollars of federal funds were combined with $2.1 million dollars made available from various state and local government sources for a total of $3.6 million. This total grew by 6.8% per annum (2.8% in inflation-adjusted terms) to reach $1.76 billion by 2006.

Since 1956, spending on total public agricultural research grew on average by 7.05% per year (2.23% in inflation-adjusted terms), slower than the corresponding rate of growth of private research 7.54% per year in nominal terms (2.72% per year in inflation-adjusted terms) (Figure 3). This means the public-sector share of total agricultural R&D drifted slightly downward over the decades, although the change in shares is comparatively small, and for most of the post-1953 period the public–private split has been quite even. In 2006, total food and agricultural R&D performed in the United States—including intramural research undertaken by the USDA and the SAESs plus the private sector—cost an estimated $9.2 billion, just 2.7% of the total spending on all areas of R&D in the United States in that year (Figure 3).

A distinctive aspect of US public agricultural R&D is the geographically dispersed nature of the performance of that research. Averaging across all 48 contiguous states, $69.8 million was spent per SAES in 2006, but with a large range around that average. California ranked first with $332 million of

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[26] To convert research spending from nominal values to real terms reflecting the purchasing power of the spending, nominal spending was divided by an index of the unit costs of agricultural research, a price index for agricultural R&D. To reflect the opportunity cost of that spending one might alternatively deflate by a general price index such as the price deflator for GDP.

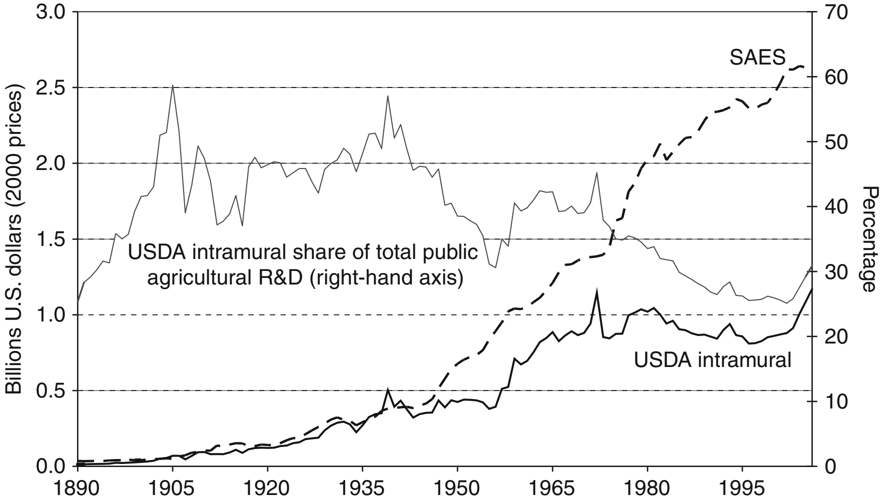

Figure 4. US public-sector agricultural R&D spending by performing agency, 1890–2006. Source: SAES series extracted from CRIS data tapes and USDA's *Inventory of Agricultural Research* publications. USDA Intramural series developed from unpublished USDA budget reports. *Notes*: SAES total includes 48 contiguous states, excluding Alaska and Hawaii which totaled $27.36 million in 2004 (or $24.5 million in 2000 prices)—just 0.85% of the 50 state total. See also Figure 5.

R&D (performed throughout the state, but with primary experiment stations located on the campuses of UC, Davis, UC Berkeley, and UC Riverside). Rhode Island ranked last, with just $4.3 million spent on research conducted by its SAESs.

5.1. Productivity orientation

Enhanced productivity as a result of agricultural R&D means that consumers have access to a more abundant, cheaper, safer, higher quality, and more diverse and convenient food supply, produced with lower stress on the natural resource base and the environment. Maintaining past productivity gains can also be privately and socially profitable. If R&D were to cease altogether, the typical scenario would be declining agricultural productivity or crop yields and rising costs, not simply a continuation of current (or baseline) yields and costs. Significant investments in maintenance research, particularly in plant breeding, plant pathology, and entomology, are required just to maintain past productivity gains. Estimates suggest that 35–70% of US agricultural research is needed to maintain previous research gains (Adusei and Norton, 1990; Heim and Blakeselee, 1986).

Classifying the reported research-problem-area (RPA) orientation of the individual research programs in each of the SAES made it possible to estimate the share of total SAES research directed to maintaining or enhancing farm productivity. In 1975, around 67% of all SAES research was so orientated. During the subsequent few years, that share fell a little, rising to a contemporary peak of 69% in 1986. However, the following two decades saw a sizable and sustained reduction in the productivity orientation of SAES research. By 2006, only 57% of SAES research sought to raise or retain past gains in farm productivity.

The productivity orientation of SAES research varies markedly among states. In 2006, barely 37% of Rhode Island's SAES research was related to productivity. At the other end of the spectrum, nearly 70% of North Dakota's research addressed farm-productivity concerns.

6. Agricultural research, invention, innovation, and adoption processes

Modeling and measuring the productivity consequences of R&D is a tricky business. The challenge in attributing productivity to R&D is to establish which research, conducted by whom, and when, was responsible for a particular productivity increase (Alston and Pardey, 2001). In other words, in modeling the effects of research on agricultural productivity the two principal areas of difficulty are in identifying the research lag structure (i.e., the "when" part of the attribution problem) and in the treatment of knowledge spillovers (i.e., the "by whom" part). The "by whom" part can have various elements, relating to knowledge spillovers among different firms within an industry, different industries within a country or other geopolitical entity, or among countries.

6.1. Temporal aspects of the R&D attribution problem

Research takes a long time to affect production, and then it affects production for a long time. Once formed, innovations and knowledge take time to diffuse and affect productivity and so the overall lag between R&D spending and productivity growth reflects a confluence between the lags involved in knowledge creation and its subsequent use. One element of the attribution problem, then, is in identifying the specifics of the dynamic structure linking research spending, knowledge stocks, and productivity.

A large number of previous studies have regressed a measure of agricultural production or productivity against variables representing agricultural research and extension, often with a view to estimating the rate of return to research.[27] Only a few studies have presented much in the way of formal theoretical justification for the particular lag models they have employed in modeling returns to agricultural research. Alston et al. (1995a) provided a conceptual framework, based on a view that agricultural production uses service flows from a stock of knowledge. This stock of knowledge is augmented by research, and a finite lag distribution relates past investments in research to current increments to the stock of knowledge.[28] However, even if knowledge depreciates in some fashion over time, under reasonable views of the nature, rate, and form of depreciation of knowledge, some effects of research will persist forever. As a practical matter, we usually end up representing these effects with a finite distributed lag that represents the confounded effects of the lags in the knowledge creation process and the dynamics of depreciation of the knowledge stock. In such a context, it is difficult to have precise views about the nature of the empirical lag relationship between research investments and productivity, in terms of its overall length and shape, apart from a perception that there will be an initial "gestation" or "invention" lag (before research has any effects), an "adoption" lag during which the lag weights rise to

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[27] A comprehensive reporting and evaluation of this literature is provided by Alston et al. (2000); see also Evenson (2002) and Alston et al. (2010).

[28] The fact that science is a cumulative process, in which today's new ideas are derived from the accumulated stock of past ideas, influences the nature of the research–productivity relationship as well. This makes the creation of knowledge unlike other production processes.

Table 1
Research lag structures in studies of agricultural productivity

Characteristic	Number of estimates	1958–69	1970–79	1980–89	1990–98	1958–98
Research lag length (benefits)	Count	Percentage				
0–10 years	253	9.7	6.2	17.9	12.7	13.4
11–20 years	537	41.9	22.0	38.8	22.8	28.5
21–30 years	376	0.0	20.7	12.0	25.9	19.9
31–40 years	178	0.0	4.3	5.6	14.3	9.4
40–∞ years	141	0.0	9.5	6.6	7.6	7.5
∞ years	102	35.5	7.5	2.9	5.4	5.4
Unspecified[a]	109	12.9	13.1	3.2	4.9	5.8
Unclear[b]	190	0.0	16.7	12.7	6.3	10.1
Total	1886	100.0	100.0	100.0	100.0	100.0

[a] Unspecified estimates are those for which the research lag length is not made explicit.
[b] Lag length is unclear.
Sources: Adapted from Alston et al. (2000).
Notes: This table is based on the full sample of 292 publications reporting 1886 observations.

a maximum, and eventually, declining weights as the impact of past research investments on current productivity fades into unimportance.

Table 1 summarizes some key features of research lag distribution models applied in studies of agricultural productivity in OECD countries. This table represents a reworked version of Table 5 in Alston et al. (2000). Until quite recently, it was common to restrict the lag length to be less than 20 years. In the earliest studies, available time series were short and lag lengths were very short, but the more recent studies have tended to use longer lags. Most studies have restricted the lag distribution to be represented by a small number of parameters, both because the time span of the data set is usually not much longer than the assumed maximum lag length, and because the individual lag parameter estimates are unstable and imprecise given the high degree of collinearity between multiple series of lagged research expenditures.[29]

Their application using long-run, state-level data on US agriculture, Alston et al. (2010) found in favor of a gamma lag distribution model with a much longer research lag than most previous studies had found—for both theoretical and empirical reasons.[30] Their empirical work supported a research lag of at least 35 years and up to 50 years for US agricultural research, with a peak of the lag distribution in year 24. This comparatively long lag has implications both for econometric estimates of the effects of research on productivity and the implied rate of return to research.

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[29] Common types of lag structures used to construct a research stock include the de Leeuw or inverted-V (e.g., Evenson, 1967), polynomial (e.g., Davis, 1980; Leiby and Adams, 1991; Thirtle and Bottomley, 1988), and trapezoidal (e.g., Alston et al., 1994; Evenson, 1996; Huffman and Evenson, 1989, 1992, 1993, 2006a,b). A small number of studies have used free-form lags (e.g., Chavas and Cox, 1992; Pardey and Craig, 1989; Ravenscraft and Scherer, 1982).

[30] The detailed arguments are laid out in Alston et al. (1995a) and Alston et al. (2008) and some earlier evidence is presented by Pardey and Craig (1989) and Alston et al. (1998). See also Huffman and Evenson (1989). Alston et al. (1998) discussed the issue of knowledge depreciation drawing on the previous literature. Noting Boulding's (1966) point that knowledge does not physically deteriorate, Griliches (1979) and Pakes and Shankerman (1987) argue that its *value* to the firm who owns a patent does depreciate, owing to displacement by new innovations and rising appropriability problems. For further discussion on the creative destruction of knowledge stocks through private R&D, see Caballero and Jaffe (1993).

6.2. More direct evidence on agricultural research lag relationships

Olmstead and Rhode (2008) challenged the view that biological innovation in US agriculture was primarily a twentieth century phenomenon, and provided compelling evidence to support their position. Clearly, much of the early development of US agriculture involved the introduction and adaptation of food and fiber species from other countries, and the adaptation of local and imported species to suit different agroecologies and to cope with coevolving pests and diseases. The benefits from many of these innovations are hidden from the analyst who observes only the pattern of average yields over time, without care to consider what yields might have been under the relevant counterfactual alternative. Constructing the appropriate with- versus without-research scenario is challenging, especially when many of the relevant determinants of incentives to develop and adopt new technologies are jointly endogenous.[31]

In this section we abstract from much of this fascinating complexity and set out to characterize the research and adoption processes for major crop varietal innovations, with a view to getting some sense of the time lags between investment in research, development, and extension and the uptake and use of the resulting innovations in farmers' fields. Drawing on Chan-Kang and Pardey (2010), we begin with a discussion of wheat varietal development, with specific attention to the duration-in-use of specific varieties both directly and through their use as parental lines for the varieties that replaced them.[32] Next, we present adoption curves for hybrid corn (in the mid-twentieth century), biotech corn (in the last decade of the twentieth century), and several mechanical technologies.[33]

6.2.1. Wheat innovations

Wheat breeding became a case study of the successful application of science to the agricultural economy following a series of important advances, especially during the 1940s. The best-known event was the identification and application of the semidwarfing characteristic to increase the harvest index or grain yield potential.[34] However, systematic breeding for resistance to various rust fungi, the development of broad-habitat varieties (e.g., improved drought or salinity tolerance), breeding for specific quality

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[31] This point was dramatically demonstrated by Olmstead and Rhode (2001) in the case of the replacement of horses and mules with tractors in a process in which the prices of both the horses and mules and their feed were jointly determined by the rate of transition to mechanical power over space and time. The same issues arise in the case of other substantial innovations—such as hybrid corn, more recently biotech corn, and most recently, corn-based ethanol—that result in significant changes in relative prices of inputs and outputs that in turn influence adoption incentives.

[32] See also Olmstead and Rhode (2002).

[33] Work in progress is extending these analyses to other crop varieties (including rice and wheat), to account specifically for the indirect adoption of varietal innovations through their use as parental lines in the case of wheat and rice and to account for adoption outside the United States, and to other innovations including mechanical innovations such as combines and irrigation

[34] Dwarfing refers to a characteristic of the wheat (and other grain) plant, where the growth of the plant's stalk is limited. Not only is more of the plant's energy directed to the production of the edible wheat grain, rather than inedible straw, but the plant is mechanically stronger. Thus, plants with larger wheat heads arising from the use of fertilizer (and irrigation) no longer lodge (or tip over), making them easier to harvest, reducing grain loss and increasing crop yields.

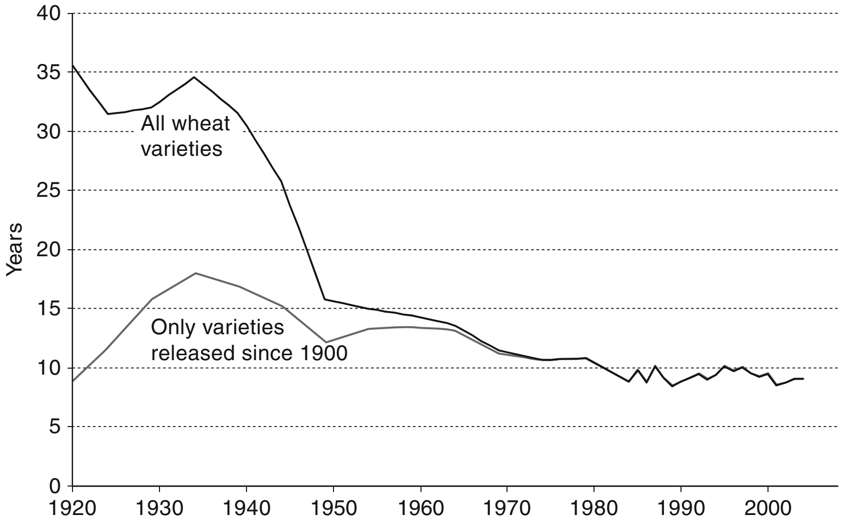

Figure 5. Wheat varietal vintages, 1991–2003. Source: Chan-Kang and Pardey (2010). *Notes*: The age of any given wheat variety was calculated by subtracting the year the variety was planted from the year it was released. To estimate the average age, each variety's age was weighted by its respective area share for each year.

characteristics (such as protein content and milling characteristics), and the development of new breeding techniques, such as "shuttle breeding," have also been important.[35]

From 1900 to 2003 a total of 1051 new wheat varieties gained commercial significance in the United States. The pace of release and uptake of new varieties varied over time. Prior to 1960 the average was 3.46 new commercial varietal introductions per year; consisting of an average of 1.55 varieties per year from 1900 to 1919, increasing to 4.43 varieties per year from 1920 to 1959. Thereafter, the pace of varietal release picked up to average 19.4 varieties per year through to 2003.

A corollary of the increased rate of varietal release was a reduction in the average age of wheat varieties, taking account of the acreage planted and the age since initial release of each variety, as shown in Figure 5. Considering all planted wheat varieties, their (area-weighted) average age was 32.7 years during the 1920s, dropping to 13.2 years by the 1960s. Counting only those varieties developed or discovered after 1900, the average age was 12.3 years by 2003. Allowing for the 5–10 years it takes to breed a new variety, these vintage profiles (measuring the average age of varieties in use in years from their date of release) underscore the notion that decades elapse before the productivity gains from investments in crop varietal research are fully realized.

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[35] Norman Borlaug's early (pre-CIMMYT) work in Mexico was initially devoted to breeding rust-resistant lines. However, breeding progress was limited to one cross per growing season. To speed things up (Borlaug, 1982, p. 69) recalls ". . . we decided to grow two breeding cycles per year, shuttling successive breeding cycles between an irrigated, sea-level environment in Sonora in the northwest corner of the country, and the cool, rain-fed highland plateau around Toluca at 2,650 meters altitude. The materials planted in November in Sonora and harvested in early May were transferred to Toluca for immediate planting. Selections at this site were in turn harvested in November and sent back to Sonora for immediate planting."

Notably, even these vintage profiles understate the length of the lags involved because they abstract from the cumulative, and intrinsically time-intensive, nature of the varietal improvement research that gives rise to these new varieties. The history of older varieties, which are found in the family trees of most of the wheat varieties bred in the United States, is reasonably well documented. For example, *Turkey Red*, a hard red winter wheat directly introduced from Turkey, and *Marquis*, a Canadian-bred (1911) hard red spring wheat crossed from *Calcutta* (an Indian landrace) and *Red Fife* (an 1842 landrace introduction from Germany) accounted for more than a quarter of all US wheat acreage around the beginning of the twentieth century.[36]

By the mid-1990s the most popular variety was *Karl*, a classic cross of well-established, short-statured plains varieties, and the second-most popular variety was *Pioneer 2375*, a hard red spring wheat released in 1989 by Pioneer HiBred International. *Pioneer 2375* represented the contemporary culmination of the spring-wheat breeding revolution and its pedigree reflects many years of intensive breeding activity. The pedigree is complex, and nearly one-quarter, or 31 of the 133 documented varietal nodes, in the *Pioneer 2375* pedigree were developed or discovered prior to 1920, more than 60 years prior to the release of the variety. Almost one-half of the documented nodes predate 1960. Notably the variety is an agglomeration of genetic material obtained from disparate locales. Only 5.3% of the documented nodes involve Minnesota material, and more than one-half of the genetic material had its origin outside the United States.

Given that the average age of wheat varieties in use has stabilized at about 10 years, if it takes 5–10 years to develop a variety, the average lag between applied varietal research investment and resulting impacts in farmers yields may be in the range of 15–25 years. However, the impacts clearly extend beyond the average lag, and perhaps more so in the past when varieties turned over more slowly. But the research effects must persist even longer (and, conversely, the implied research lag must be even longer) given the role of today's varieties as parents of the varieties that will replace them, and the persistence of the impacts through the offspring (and across subsequent generations) of the research that created the parents. As the example of *Pioneer 2375* shows, the persistent effects of a varietal innovation can last for decades after the variety itself ceases to be grown in farmers' fields.

6.2.2. Hybrid-corn technology

Griliches' (1957) analysis of the generation and dissemination of hybrid-corn technology throughout the United States was a seminal study in the economics of diffusion and the spatial spillover of an agricultural technology. Here, we revisit and update some aspects of that analysis, focusing on the implications for R&D lags. The relevant history goes back thousands of years to the beginning of agriculture. Even if we focus on the modern, scientific era and the relatively applied work focused on hybrid corn, the story began at least 20 years before commercial planting of hybrid corn became significant, and 40 years before the adoption process had been completed, in the sense that the percentage of corn planted to hybrids had reached a stable maximum.[37]

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[36] A "landrace" refers to a farmer-bred variety.

[37] In 1918, Donald F. Jones working at the Connecticut Agricultural Experiment Station suggested the use of the double-cross (involving a cross between two single inbred lines of a particular crop variety) as a practical and effective means of realizing hybrid vigor in corn that George H. Shull and others had begun pursuing using single-cross methods a decade earlier. Through an expanding number of inbreeding projects at various state experiment stations, and research conducted by the USDA's Bureau of Plant Industry, seeds developed with this technology were gradually bred for various local agroecologies and began spreading among the various states, beginning in the early 1930s in Iowa. Thus, the R&D or innovation lag was at least 10 years and may have been 20–30 years.

Figure 6, Panel A, includes an updated and extended version of the adoption curve for hybrid corn, as initially presented by Griliches (1958) and revised by Dixon (1980).[38] By 1950, 80% and by 1960, almost all of the corn grown in the United States was hybrid corn. Looking across all the states, the technology diffusion process was spread over more like 30 years, reflecting the envelope of adoption processes that were much more rapid in any individual state.

If we think of the entire research, development, and adoption process for hybrid corn as having begun as late as 1918 (if not in the early 1900s with Shull and others), then the widespread adoption of hybrid corn by 1960 took place over a period of at least 40 years and possibly decades longer. Moreover, hybrid corn continues to be grown today, in the range of 100 years since the focused research that led to those initial innovations began to take hold. It seems reasonable to imagine that a relatively long overall R&D lag, with a significant gestation lag, would be required to represent the links between investment in hybrid-corn research and resulting impacts on aggregate agricultural productivity, though it is not clear just how long those lags should be nor what shape the lag distribution should assume.

6.2.3. Biotech corn innovations

The most recent revolution in corn-seed technology began to take effect in farmers' fields half a century after the hybrid-corn revolution. Modern biotechnology encompasses a range of innovations, including genetically engineered (GE) crop varieties. Among these, corn, soybeans, cotton, and canola are the most important biotech crops.[39] Corn was one of the first biotech crops to achieve commercial success. The two main types of innovations in corn and the other main biotech crops confer either (a) herbicide tolerance (in particular tolerance of the broad-spectrum herbicide glyphosate marketed by Monsanto originally under the brand name Roundup®), allowing enhanced weed control at lower cost, or (b) insect pest resistance, achieved by inserting genes from *Bacillus thuringiensis*, or *Bt*, a bacterium that produces insecticides naturally, such that the corn plants themselves express the insecticide. In fact, different types of *Bt* corn have been introduced with resistance to different insect pests, including the European corn borer (first released for commercial use in 1996) and the Western corn root worm (first released for commercial use in 2006), among others. These can be "stacked" with one another as well as herbicide tolerance ("roundup-ready" corn was first released for commercial use in 1996), to achieve multiple pest resistance jointly with herbicide tolerance.[40] Hence, biotech corn is not a single, simple innovation.

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[38] Dixon (1980) used additional data on the uptake of hybrid corn, beyond that reported by Griliches (1957), to reestimate the rate of acceptance and the ceiling rate of adoption of hybrid corn. Dixon's results were ". . . supportive of Griliches' finding of a close association between the variability in the rates of diffusion across states on the one hand, and yield per acre and acres per farm on the other (1980, p. 1,460)." In a rejoinder to Dixon's paper, Griliches observed ". . .my model (as of 1955–57) is clearly wrong in retrospect both because of its assumption of a constant ceiling [rate of adoption] and because the underlying process did not follow a fixed logistic curve exactly.. . . I would now rectify the model so that the ceiling is itself a function of economic variables that change over time (1980, p. 1,463)."

[39] The perception of market resistance (from consumers or political organizations) has prevented the development and use of biotech varieties for major food crops such as rice and wheat while also slowing the development and use of biotech varieties for feedgrains, oilseeds, and fiber crops. Pardey et al. (2007) and the references therein give details on the uptake of biotech crops in an international context.

[40] The first herbicide tolerant and insect resistant corn varieties were approved for use in mid-1995. Since then a further 14 different regulatory approvals have been granted for genetically engineered corn varietal innovations with tolerance of different herbicides, resistance to different insect pests, or some combination. Significant adoption of each of these varieties began in the year when its regulatory approval was granted. These details were provided by Nicholas Kalaitzandonakes (Personal Communication, September 2008) and Eric Sachs (Personal Communication, November 2008).

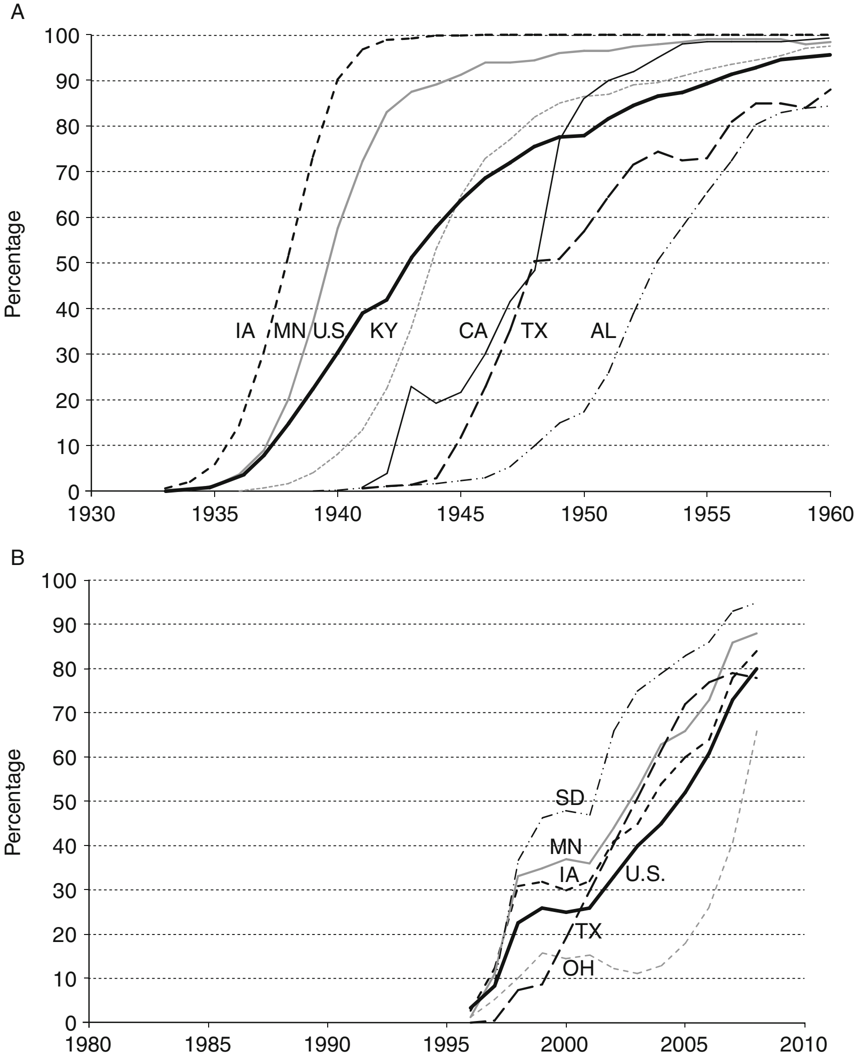

Figure 6. Uptake of biological technologies for corn. Source: Alston et al. (2010). Panel (A): Area shares of hybrid corn obtained from *USDA Agricultural Statistics* (various years). Panel (B): Genetically engineered varieties data calculated by Pardey from confidential data from Doane for the pre-2000 period and USDA-ERS data on biotech crops (http://www.ers.usda.gov/Data/BiotechCrops/) for the post-1999 period combined with data on crop area harvested from *USDA Agricultural Statistics* (various years). *Notes*: For panel (B), state specific rates of change in area shares for the pre-2000 years were used to backcast the corresponding state series obtained from the publicly reported USDA-ERS data.

Rather, the research to achieve these new outcomes separately, to combine them with one another, and to incorporate them into new corn varieties suited to different agroecologies or with enhanced other characteristics, has continued in parallel with the adoption process that started in the 1990s.

In Figure 6, Panel B, we can see the pattern of uptake of biotech corn among the main US corn-growing states and in the nation as a whole. GE corn was first planted on US farmers' fields in the mid-1990s. The adoption-cum-diffusion process for GE crops is not yet complete, the technology itself is continuing to evolve, and the maximum adoption rate has not yet been achieved, but by 2008, 80% of US corn acreage was planted to GE varieties. Like hybrid corn, biotech corn has been adopted at different rates in different states, but perhaps for different reasons.[41] This as-yet-incomplete process over less than 15 years represents only part of the relevant time lag. To that we must add the time spent conducting relatively basic and applied research to develop and evaluate the technology, and the time (and money) spent after the technology had been developed to meet the requirements for regulatory approval by a range of government agencies (e.g., Kalaitzandonakes et al., 2006).

Compared with the adoption-cum-diffusion process for hybrid corn within the United States (Figure 6, Panel A), the process for biotech corn appears to have been a little faster (Figure 6, Panel B). The main difference may be that all states began to adopt together, without the slower spatial diffusion among states that characterized hybrid corn, possibly because of improved communications and farmer education, and structural changes in the seed production and distribution sectors. Thus, biotech corn achieved 80% adoption within 13 years of the first commercial release of the technology compared with 19 years for hybrid corn. However, other prerelease elements of the process may be getting longer. For instance, the process of regulatory approval may have added a further 5–10 years to the R&D lag (and this regulatory approval lag for biotech crops appears to be growing over time). Given a range of 10–20 years spent on R&D to develop the technologies that enabled the creation of biotech crops, and then the time spent to develop the initial varieties and improve them, the overall process of innovation in the case of biotech corn may have taken 20–30 years so far.[42] The implied R&D lag may be in the same range as that for the hybrid-corn varietal revolution, upon which this latest corn varietal revolution is building.[43]

6.2.4. *Uptake of other innovations*

In addition to biological innovations, of which genetic improvement of crop varieties has been an important component, agriculture has adopted many other types of innovations. *Mechanical technologies* (especially labor-saving machines for cultivation and harvest and the like), transformed agriculture especially in the early part of the twentieth century; *chemical technologies* such as those embodied in fuels, synthetic fertilizers, pesticides, and growth promotants, had their biggest impacts in the second half of the twentieth century; *information technologies,* involving computers, electronics, robotics,

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[41] The demand for biotech crop varieties varies among locations, depending on the prevalence of weed and pest problems that they address, on the price charged by the technology providers, and on the perceived market discount or other penalty from the use of the biotech crop variety. Thus some farmers in some locations will never adopt biotech crop varieties, whereas hybrid corn varieties are more generally superior, given local adaptation, and they do not entail risk of market discounts or other side effects.

[42] A more complete analysis would also account for the international adoption of these technologies and the implications for the United States through the resulting price impacts.

[43] The cumulative nature of the crop improvement process is clearly evident in the case of corn; the GE innovations of the late twentieth century such as herbicide tolerance or insect resistance are themselves being bundled into hybrid corn varieties that are the progeny of an early twentieth century innovation.

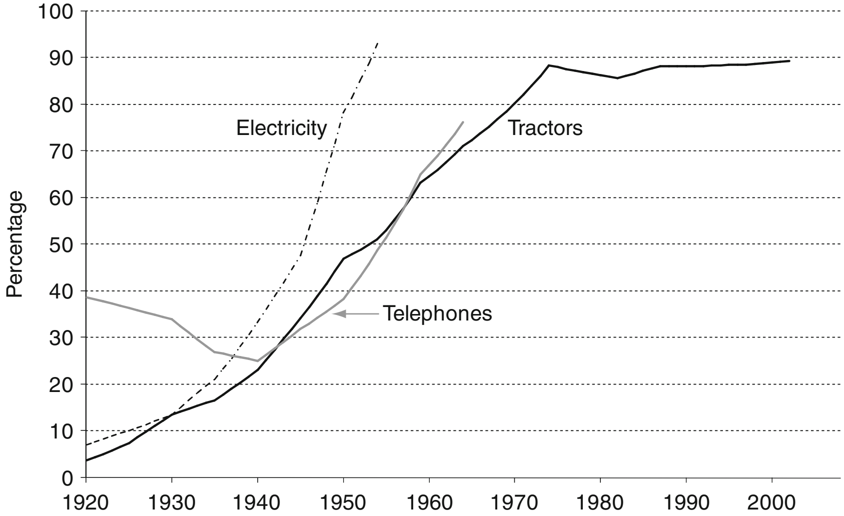

Figure 7. Uptake of agricultural technologies in the United States. Source: Alston et al. (2010) based on the US Agricultural Census (various years). *Notes*: Plots represent linear interpolations between adjacent agricultural census years. The shares were constructed from data on the number of farms reporting tractors, electricity, telephone, and the total numbers of farms.

remote sensing, and geographic information systems (GIS) technologies, are mainly a relatively recent and contemporary phenomenon, though the telephone and telegraph can be seen as earlier examples.[44] Each of these broad categories, like biological innovations, includes a broad range of different types of specific innovations, and we have only partial information on the research and adoption processes. Relatively good information is available on the uptake by farmers of some specific, important innovations that can serve as illustrative examples. Figure 7, Panel A, shows the pattern of adoption of three types of innovations on US farms: tractors, electrification, and telephones.[45]

In 1920, 7% of US farms had electricity. This percentage grew in a classic sigmoid shape to over 90% within the following 30 years. The adoption process for telephones was much different. The percentage of farms with telephones fell from 40% in 1920 to 25% in 1940, reflecting, perhaps, the effects of the Depression and World War II.[46] Then from 1940 forward the number of farms with telephones grew

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[44] Olmstead and Rhode (2000, 2008) provide a broader coverage of the transformation of American agriculture during the years 1910–1990. They give some emphasis to the very significant role played by technological innovation, but not exclusively, and their coverage of mechanization, transportation and communication, and the related work by economists, is more complete than ours, which is deliberately selective.

[45] These are national aggregate percentages. We also have data at the state level and data on other innovations (such as the adoption of combines) that are the subject of continuing research.

[46] Both the telephone and electricity required investment in infrastructure. Public policies, notably New Deal programs including the Rural Electrification Administration (REA) and the Tennessee Valley Authority (TVA) affected the development of the supply of electricity and its availability in rural areas (see, e.g., Emmons, 1993). The availability of these technologies and their uptake by individual farmers depended on other economic circumstances as well. Goldin (1947) describes the moribund state of the US telephone industry during the 1930s. See also studies cited by Olmstead and Rhode (2000).

roughly in line with the numbers of farms with tractors, from around one-quarter to about two-thirds by 1960. All of these changes reflect changes in both the numerator and the denominator of the measures of technology use per farm, because the numbers of farms were changing rapidly, especially during the latter half of the twentieth century; falling from 6.4 million in 1920 to 6.0 million in 1940, then dropping to 3.6 million by 1960. Moreover, it was the smaller and economically less-successful farms that were going out of business and the remaining farms were becoming larger and changing in other ways, factors that would have been strongly related to their use of newer technologies.

The case of tractors warrants particular attention because we have more and better data on the use of tractors on farms, and because the displacement of horses and mules transformed agriculture so dramatically.[47] Figure 7 shows that the adoption process extended over 50 years, from before 1920, when less than 5% of farms had tractors, through to the early 1970s, when the fraction of farms with tractors stabilized at almost 90%. This simple picture conceals many complications, such as those associated with the changing numbers of farms and the changing definition of what constitutes a farm for statistical purposes. It is an aggregation across different states and different agroecologies and production systems that may have adopted tractors sooner or later, faster, or slower. It is also an aggregation across types of tractors. Over the 50 years to 1970, and the 40 years since then, tractors have continued to evolve and improve in many ways.[48] Thus, it could be quite misleading simply to count tractors at a point in time as well as over time, when the characteristics of tractors are so variable. And, like biotech corn, it would be a mistake to conceive of the tractor as an episodic innovation that was introduced at a point in time and gradually adopted in unchanged form from that point on. Rather, the tractor represented a continuum of innovations, the adoption of which both enabled and was enabled by the progressive consolidation of farms into larger units that could exploit the economies of size, scale, and specialization afforded by mechanization.

Comparing the adoption curves for corn varieties in Figure 6 with those for tractors, electricity, and telephones in Figure 7, one common point emerges. The adoption process for agricultural innovation takes time—in the range of 15–30 years for broad classes of varietal innovations (such as hybrid corn or biotech crops at the level of the nation, as compared with individual crop varieties in a particular locale), and in the range of 30–50 years for major mechanical innovations (such as tractors and combines) and for other significant technologies (such as the telephone and electricity). These facts alone suggest that the time lags between investing in research that contributed to the development of this technology, and reaping the resulting benefits, could be quite long. To the lags from adoption must be added the R&D lags which themselves are hard to pinpoint but potentially also very long.

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[47] Olmstead and Rhode (2001) provide an insightful analysis of the adoption of tractors in US agriculture, drawing out the role of induced changes in prices of horses and mules over space and time, and the feed grains they both produced and consumed; price changes that were exogenous to individual farmers as determinants of their adoption decisions but endogenous to the sector as a whole. See also David (1996).

[48] Improved features include such things as pneumatic tires, suspension, hydraulic systems, power take-offs, fuel efficiency, horsepower, driver safety and comfort (including cushioned seats, air conditioned cabs, stereo systems), four-wheel drive, and computerized driving systems.

6.3. Spatial aspects of the R&D attribution problem

Compared with the research lag structure, the issue of spatial attribution has received less attention in the literature on agricultural R&D, and has been approached differently in the literature on industrial R&D. In the more-recent literature, however, increasing attention has been paid to accounting for the fact that knowledge created within a particular geopolitical entity can have impacts on technology elsewhere, with implications that may matter to both the creators of the spillouts and the recipients of the spillins. Some of the earliest work on these matters was done in applications to agriculture.

Griliches' (1957) analysis of the generation and dissemination of hybrid-corn technology throughout the United States was a seminal study in the economics of diffusion as well as the spatial spillover of an agricultural technology.[49] The first hybrid-corn seed sales were in Connecticut in 1920 and in Iowa four years later, but it took until the early 1930s before commercially successful seed in sufficient quantities became more-widely available and the technology took off, initially in the Corn Belt states and then spreading farther afield. Iowa had 10% of its corn acreage planted to hybrids in 1936 (with 90% of its corn acreage so planted just 4 years later), while in Alabama—a state with distinctive agroecological attributes compared with the principal Corn Belt states—it took until 1948 before 10% of its corn acreage was under hybrids. This reflected lags in the "availability" of hybrid seed suitable for a particular state (or for the agroecologies dominant in that state) and lags in the uptake or "acceptance" of the technology once suitable seed became available.

Hybrid-corn technology, and Griliches' study of it, graphically demonstrated the spatial spillovers of an important biological innovation, and the roles of federal and state public laboratories as well as private firms in the spread of the technology. While much can be learned from studies of spillovers of particular technologies, they provide only a partial picture of the spillover consequences of R&D.[50] Other studies have sought to assess the overall effects of agricultural research on productivity with regression-based methods using more aggregate (region- or state-specific as well as national) measures of R&D.[51] Among these, for example, Huffman and Evenson (1993) found that a sizable share (upwards of 45%) of the benefits from research conducted in US SAESs was earned as interstate spillovers.

Whether they were concerned with spillovers or not, the past studies have imposed implicit or explicit assumptions about the spatial spillover effects of agricultural research based on geopolitical boundaries. For example, most past studies of the effects of US agricultural research on productivity have implicitly assumed that agricultural research is totally fungible, such that US national agricultural output depends on the national aggregate of US spending on public agricultural R&D, regardless of where it was spent

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[49] A large literature emerged on the economics of adoption, with numerous studies on the uptake of new innovations in agriculture. See, for example, Lindner et al. (1979), Feder and O'Mara (1982), and Johnson and Ruttan (1997). Feder et al. (1985) and Sunding and Zilberman (2001) review much of this literature.

[50] For example, Evenson and Kislev (1973, 1975) analyzed spillovers related to wheat and maize research, Araji et al. (1995) looked at spillovers regarding potato research, and Mareida et al. (1996) and Byerlee and Traxler (2001) investigated wheat spillovers.

[51] Alston (2002) reviewed the literature on agricultural technology spillovers, with particular attention to the US applications. See also Pardey et al. (1996) who did a detailed analysis of the economic effects of rice and wheat varieties developed by international research centers in the Philippines and Mexico that spilled into the United States and Pardey et al. (2006a) who did an economic assessment of the sizable international crop varietal spillovers into Brazil.

or by whom (e.g., Alston et al., 1998; Chavas and Cox, 1992; Evenson, 1967; Griliches, 1964; White and Havlicek, 1982).

In contrast, some studies at the level of individual states proposed that research efforts by individual states have spillover effects only among states within the same (subnational) geopolitical region, while research outside a region does not affect its agricultural productivity.[52] The grouping of states into regions and the specifics of the spillin variables vary among these studies. For instance, Khanna et al. (1994) grouped states into six regions according to a classification scheme devised by the Economic Research Service of the USDA. For each state in each region a spillover variable consisted of the pool of research done by other states in the same region, meaning that research done by states outside a particular region was of no consequence for states within that region. Similarly, for each of the 48 contiguous states in their study, Yee and Huffman (2001) constructed a spillin stock of publicly generated knowledge as the sum of public research stocks of all states in the relevant region less the state's own research stock. Several other studies, beginning with Huffman and Evenson (1989), incorporated geoclimatic information while retaining the restriction that technology spillovers occur only among neighboring states within contiguous geopolitical regions.[53]

Many studies, however, simply ignored the effects of research in other states or by the federal government (e.g., Alston et al., 1994; Leiby and Adams, 1991; Norton and Ortiz, 1992), and almost all of the regression-based studies of agricultural R&D have ignored the possibility of international spillovers, unless they were specifically emphasizing that possibility. Two exceptions are the studies by Bouchet et al. (1989) and Schimmelpfennig and Thirtle (1999).[54] Looking more broadly at the literature, few studies of national systems, irrespective of the method used, have allowed for either spillins or spillouts—in their meta-analysis, Alston et al. (2000) identified less than 20% of studies allowing for *any* spillovers.

The modeling decisions—either to ignore spillovers or represent them using measures based on physical proximity—have been at least to some extent driven by the limitations of available data and the requirements for parsimonious models. Even when we are conscious of the possibility of interstate or international spillover effects (and not totally hamstrung by data limitations), it is not clear what we ought to do about them. Clearly, however, restrictive assumptions are inevitable.

7. Innovation outcomes

Innovation in agriculture has played a central role in human progress, and in some cases has served as a crucial step in the process of economic development. But like any important change in any part of the economy, agricultural innovation has multidimensional impacts, and some aspects of agricultural innovation have not been welcomed by all of those affected.

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[52] Citation patterns in patent applications and in professional published literature suggest spatial spillovers are much more pervasive.

[53] The same set of constructed spillover weights were used subsequently by Huffman and Evenson (1992, 1993, 2001, 2006a,b), Huffman and Just (1994), and McCunn and Huffman (2000).

[54] On the other hand, studies of the effects of the CGIAR centers on agricultural productivity in adopting countries using other than regression methods have emphasized the spillins of technology (e.g., Brennan, 2007; Brennan and Bantilan, 1999; Brennan and Fox, 1995; Brennan et al., 1997; Pardey et al., 1996). Alston (2002) reviewed these studies. Brennan (2007) reports a more-recent application to wheat spillovers from CIMMYT to Australia.

Throughout the recorded history of agriculture, issues have been raised that relate to food safety, farm worker safety, and the environment, that imply a demand for regulation over the types of technology that farmers or food processors may adopt. Some innovations might pose risks to the environment that are not fully recognized by farmers or others, and whose consequences may not be fully reflected in markets. For instance, in some places land clearing and irrigation have led to soil salinity and other land degradation problems faced by farmers and others sometimes far afield and far downstream from the source; in some cases the accumulation of chemical pesticides and fertilizers in the soil or groundwater have had unintended harmful effects on beneficial species or human health; modern livestock production systems use intensive housing and feeding structures that have been questioned on animal welfare grounds. Some of these consequences have been shown to be real and are the subject of regulation (such as the effects of DDT on birds, especially raptors, and the ban on its use as a pesticide in the United States), but in many cases the opposition to agricultural innovation has been without scientific support (such as the contemporary opposition to certain genetically modified crop varieties that have been demonstrated to be at least as safe as conventional technologies, or the opposition to the introduction of milk pasteurization early in the twentieth century or food irradiation technology, later in the twentieth century). As history has shown, because agricultural innovations have multidimensional effects, many of which are very difficult to anticipate and quantify, important innovations can be expected to face spirited opposition even if (and perhaps especially when) scientific evidence on the consequences is not available, and decisions about whether to allow particular innovations must be made based on only partial information about the consequences. In some cases, as has happened in the past, opposition to particular technologies on the grounds of nonmarket impacts will turn out to be warranted; but counter-examples are probably more common.

In addition to external or off-site impacts, agricultural innovation also has had important distributional consequences through its influence on the supply of different farm outputs, the demand for land, labor, and other inputs used by farmers, and their prices. A primary effect of agricultural innovation has been to release labor and other resources for other purposes, a consequence that is seen as a virtue by many economists. But some labor-saving agricultural innovations have attracted political or legal action from displaced workers who felt disadvantaged as a consequence.[55]

Labor-saving innovations in particular have contributed to changes in the nature of farms and farming, which have become larger and more specialized, with implications for the demand for infrastructure and services to be provided in rural communities. Many commentators have lamented the progressive reduction in the number of farms and the loss of so-called family farms, as well as the decline in rural communities and the loss of small towns, changes that have accompanied modernization of farming around the world. Certain other kinds of innovations are questioned for other reasons, some of which are also connected to a sentimental concept of farms and the farming way of life that may never have really existed.

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[55] The adoption of the mechanical tomato harvester in California is a good example. Schmitz and Seckler (1970) suggested that social costs from the displacement of labor offset the benefits from the technology. Martin and Olmstead (1985) and others have pointed out that (a) the termination of the Bracero program and the associated withdrawal of labor created the demand for the innovation, rather than the converse, and (b) in an appropriate counterfactual scenario, California's development and adoption of the mechanical tomato harvester actually increased the total employment of labor in the California tomato industry.

In this section we review the broad patterns in agricultural innovation in terms of its impacts on the use of land and labor and other resources, and the overall productivity of agriculture, and its implications for the mix of inputs used (the factor bias of technological change) and the output mix. Then we consider measures of the benefits.

7.1. Cost-push or demand-pull factors affecting innovation

In a common vision of technological change, new technologies come to agriculture from the rest of society through its financing of research in colleges and governmental research agencies. Hence, technological change is *exogenous* to agriculture and, on this view, especially as a result of the introduction of machines, labor has been driven from agriculture by government-sponsored R&D. An alternative view is that technological change in agriculture has been motivated by technical change in manufacturing that drew labor from agriculture, driving up wage rates, and creating a demand for labor-saving innovations. Almost surely both types of forces have been at work, with one more important than the other in different places and times. Kislev and Peterson (1981, p. 564) concluded:

> *"Farmers demanded new and better machines because the cost of farm labor, both the opportunity cost of family labor and the wage of hired labor, increased relative to the price of machinery services. Machinery manufacturers responded to this increase in demand by expanding capacity through investment in both research and development and plant and equipment.... Thus, as we read the evidence, the technical change that encouraged farm mechanization occurred mostly in the manufacturing sector."*

7.2. Factor-saving innovation

Comparative research on the rate and direction of productivity growth in agriculture has gone through three stages (Ruttan, 2002, pp. 165–167). Initially, efforts were directed to measurement of partial productivity indexes, such as output per worker and per acre (or per hectare). Intercountry and time-series comparisons of output per unit of land and labor were first assembled by Colin Clark in his pioneering study, *The Conditions of Economic Progress* (1940). In the late 1960s, Clark's intercountry comparisons were updated by Yujiro Hayami and associates (Hayami, 1969; Hayami et al., 1971). These early partial productivity studies indicated exceedingly wide differences in land and labor productivities, both among countries and major world regions. Recent trends in land and labor productivities indicate that these trends have persisted (Hayami and Ruttan, 1971; reprinted 1985. pp. 118–133; Pardey et al., 2007).

In Figure 8, labor productivity (output per worker) is measured on the horizontal axis and land productivity (output per hectare) is measured on the vertical axis. The diagonal lines trace land–labor factor ratios (hectares of agricultural land per worker). The country and regional lines indicate land–labor trajectories for specific countries or regions. The several country and regional growth paths fall broadly into three groups: (a) a land-constrained path in which output per hectare has risen faster than output per worker; (b) a land-abundant path in which output per worker has risen more rapidly than

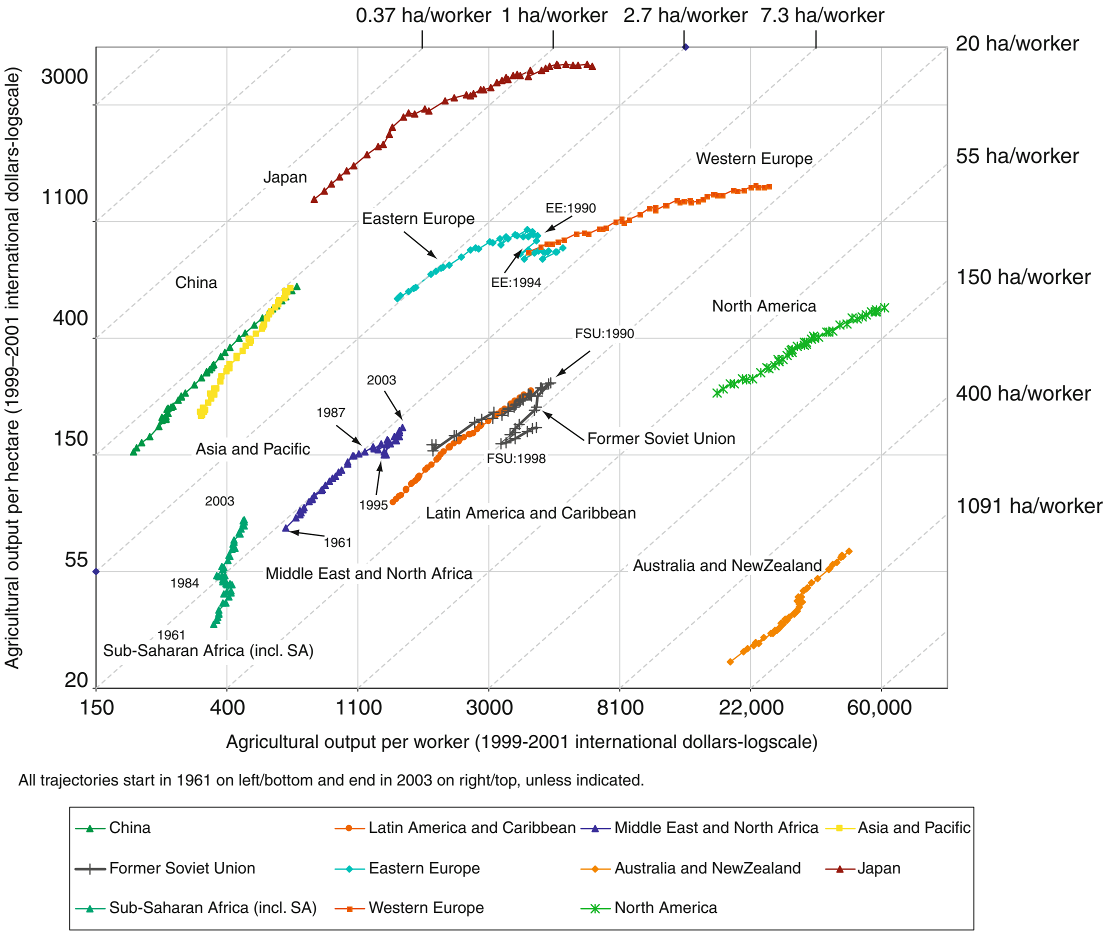

Figure 8. Factor bias and rate of technological change in global agriculture. Source: Updated version of Figure 4 from Pardey et al. (2007).

output per hectare, and (c) an intermediate path in which output per worker and per hectare have grown at somewhat comparable rates. Hayami and Ruttan (1971) characterized the vertical path as the "biological technology" path and the horizontal trajectory as the "mechanical technology" trajectory. During the later stages of development as the price of labor rises relative to the price of land the growth path tends to shift in a labor-saving direction.

Partial productivity ratios such as those shown in Figure 8 were used by Hayami and Ruttan (1970, 1971) in their initial tests of the induced technical change hypothesis. An important implication of the data presented in Figure 8 is that the changes in productivity over time and the differences across regions cannot be accounted for by simple technological evolution or technology transfer. In Figure 8 logged ratios of agricultural output per hectare (land productivity) are plotted on the horizontal axis against output per worker (labor productivity) on the vertical axis for nine regions of the world as well as the Former Soviet Union and Japan (together representing 231 countries) for each of the years 1961–2003. All of the productivity paths move in a northeasterly direction starting in 1961 and ending in 2003, indicating increasing productivity. A longer productivity locus means a greater *percentage* change in productivity. China, and the Asia and Pacific region experienced the fastest rate of growth of land productivity (respectively, 3.4 and 2.8% per year), and the Former Soviet Union the slowest (0.08%). With a rapid exodus of labor from agriculture, Japan's labor productivity grew the fastest (5.15% per year) and sub-Saharan Africa (including South Africa) the slowest (0.35%).

As noted, the diagonal lines indicate constant factor (specifically, land-to-labor) ratios. When a region's productivity locus is flatter than these diagonal lines (e.g., Japan in more recent decades), it indicates an increase in the number of agricultural hectares per agricultural worker in that country as we move from left to right: in Japan's case from 0.59 hectares per worker in 1961 to 1.57 hectares per worker in 2003. Land–labor ratios in Australia and New Zealand have changed little, whereas they have risen by some 73% in North America. They also rose, albeit very slowly, for the Latin America and Caribbean region, consistent with the region's labor productivity growing slightly faster than its land productivity. Sub-Saharan Africa has become much more labor intensive so land–labor ratios have declined. In 1961 the region had 10.5 hectares per agricultural worker, but by 2003 the land–labor ratio had nearly halved to 5.4 hectares per worker.

7.3. Cochrane's treadmill and other distributional stories

The distribution of the benefits and costs of innovation has been the subject of a reasonably large number of articles within the agricultural economics literature. Beginning with Cochrane (1958, 1993), some economists have argued that agricultural innovation is a treadmill for farmers with an implicit (sometimes explicit) notion that technological change in agriculture has made farmers worse off. In Cochrane's analysis, only the earliest adopters could benefit from new technology, and their benefits were fleeting. Eventually the price-depressing effects of increased output would offset the gains. Those who were slow to adopt or did not adopt would lose. He characterized the process as a treadmill that farmers must tread to survive but that involved unhappy consequences for agriculture.

As a description of events, the treadmill argument is questionable since it rests on doubtful assumptions about the form of technical change, its causes, and the nature of demand for farm products, and an unduly narrow view of the potential benefits from research. The argument has greater content in a closed-economy model, or, perhaps, when taking a global perspective, than from the point of view of national (or state) research benefits when allowance is made for international (or interstate) trade. To the extent that research-induced technical change drives prices down, consumers benefit and producer benefits are diminished, and those producers who are relatively unable to exploit the new technology are liable to be net losers. But losses to producers as a group are not possible unless demand is inelastic; an unlikely prospect for most US tradable agricultural products (e.g., Alston et al., 1995a). Indeed, in some cases the United States cannot influence world prices at all, so producers cannot be harmed. For most other traded US agricultural commodities the predominant although not universal view among agricultural economists (supported by the carefully conceived empirical literature) is that demand is elastic, often highly elastic so that the necessary condition for producer losses is usually not met (e.g., Gardner, 1988). Aggregate producer losses are unlikely, even in the exceptional cases when the relevant demand is inelastic.

This does not mean that all producers necessarily benefit. Certainly, those farmers who don't adopt an innovation lose when others do adopt and consequently drive down the product price; and those farmers who do innovate have to keep innovating to stay ahead of the falling prices caused by collective innovation. But in this dynamic context, the process of innovating can still be beneficial for farmers, and the indications are that in most cases farmers, as a group, have shared in the benefits from agricultural innovation (e.g., see Alston and Pardey, 1996).

The issue is not whether research generates net benefits but how those benefits are distributed between producers and others. In a conventional comparative-static representation of the market-wide impacts of adoption of a process innovation, farmers will benefit if their average costs fall by more than the price does. Whether this will happen depends on the nature of the demand for the product and the nature of the innovation—in particular, farmers are less likely to benefit from an innovation when demand is less elastic. Consumers certainly have benefited but questions remain about the distribution of the remaining benefits (and costs) of innovation between farmers and others including landowners, other suppliers of inputs used by farmers such as farm labor, agricultural technology providers, and other agribusiness firms. For instance, Herdt and Cochrane (1966) suggested that even those benefits from technological change that went to the farm would not go to farmers: "... with the conclusion that technological advance benefits, not the farm operator or the farm manager, but the farm land owner (p. 243)." The empirical literature is not conclusive on this question mainly because the estimates of benefits in the literature have required the use of assumptions that determine, in advance, this aspect of the results. A definitive test has not yet been devised to answer the question: do farmers benefit from agricultural innovation? To say how much is even harder.

7.4. Nonmarket research effects

Environmental and natural resource issues have become a major concern for both the general public and for agricultural researchers. These issues include concerns about wilderness and species preservation, pollution of groundwater with pesticides and nitrogen, and implications of pesticide and herbicide residues for safety of farmers, other agricultural workers, and consumers (e.g., Antle and Pingali, 1994). The environmental impacts of agriculture, and of changes in agricultural technology, have not always been of such policy relevance.[56] Consequently, the environmental impacts of agricultural technology, and the benefits from resource preservation or greater environmental amenities, have not been adequately accounted for in either rate-of-return studies or in productivity growth statistics. Economists have tended, as a result, to overestimate productivity growth in general and to overstate the benefits from certain types of R&D that enhance conventionally measured productivity. Alston et al. (1995b) discuss some of the issues. Environmental effects usually are not reflected in the analysis of supply and demand in a commodity market and, therefore, environmental effects are nonmarket benefits from

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[56] Some environmental and natural resource conservation aspects have not been so neglected. For instance, the US Soil Conservation Service was established many years ago.

R&D. Environmental and other nonmarket effects are difficult to capture in the conventional measures of benefits from agricultural research. Further, benefits from research related to environmental or resource issues may be particularly difficult to assess, even when such research does affect agricultural markets in ways similar to more traditional research.

Research on resource or environmental topics may enhance agricultural productivity and reduce production costs. However, such productivity consequences are often difficult to measure because the processes of environmental degradation are difficult to quantify and the productivity effects are gradual—although potentially profound. In addition, measured productivity may not capture some of the important consequences of the research; for example, research into removal of selenium from the soil has complex multiple payoffs to agricultural productivity, but also benefits to wildlife. Some benefits are partially measurable as shifts in the trend productivity growth rate. Preventing productivity from falling is often more important, and such effects are not adequately represented in common estimates of rates of return. The relevant comparison is between the trends of productivity with and without such research and these are difficult to assess. The problem is similar to assessing the payoff to "maintenance" research (discussed above), but much more difficult because environmental or regulatory factors have complex and often poorly understood dynamic effects.

Agricultural research on environmental and resource topics has become increasingly aimed toward helping agriculture respond to added regulations more efficiently. As the public demand for more environmental regulations continues, agriculture requires alternatives to current practices that will allow growers to maintain productivity in the face of changing and more restrictive regulations. Without ongoing research, it is difficult to preserve positive trends in productivity, let alone maintain past productivity gains, in the face of new regulatory constraints. These regulations are a challenging part of the economic environment of modern agriculture and research that aids agriculture's response contributes to long-term productivity as well as to other social goals. Agricultural research also contributes directly to improved environmental and recreational amenities. Benefits of this type are also difficult to measure and do not easily translate into quantifiable economic gains. Hence, environmental improvements that benefit the general public are not often represented in estimates of economic well-being, let alone the rates of return to agricultural research.

7.5. *Rates of return in the literature*

Agricultural economists have invested extensively in quantifying the payoffs to agricultural R&D, but for the most part these studies have referred to total benefits to the relevant society, rather than to particular groups in society. Alston et al. (2000) conducted a meta-analysis of 292 studies that reported estimates of returns to agricultural R&D, and reported an overall mean internal rate of return for their sample of 1852 estimates of 81.3%, with a mode of 40%, and a median of 44.3% (see Table 2). After dropping some outliers and incomplete observations, they conducted regression analysis using a sample of 1128 estimates with a mean of 64.6%, a mode of 28%, and a median of 42.0%. They found results that were generally consistent with expectations but in many cases they could not distinguish statistically significant effects on the estimated rates of return associated with the nature of the research being

Table 2
Lag structures and rates of return to agricultural R&D

	Estimates		Rate of return				
Characteristic	Number	Share of total	Mean	Mode	Median	Minimum	Maximum
	Count		Percentage				
Research lag length							
0–10	370	20.9	90.7	58.0	56.0	–56.6	1219.0
11–20	490	27.7	58.5	49.0	43.7	–100.0	677.0
21–30	358	20.2	152.4	57.0	53.9	0.0	5645.0
31–40	152	8.6	64.0	40.0	41.1	0.0	384.4
40–∞ years	113	6.4	29.3	20.0	19.0	0.3	301.0
∞ years	57	3.2	49.9	20.0	35.0	–14.9	260.0
Unspecified	205	11.6	48.7	25.0	34.5	1.1	337.0
Unclear	27	1.5	43.1	27 and 60	38.0	9.0	125.0
Research gestation lag							
Included	468	59.2	65.5	46.0	47.1	–14.9	526.0
Omitted	314	39.7	96.7	95.0	58.8	0.0	1219.0
Unspecified or unclear	8	1.0	25.1		24.1	6.9	55.0
Total	790	100.0	77.5	46 and 58	50.2	–14.9	1219.0
Spillovers							
Spillins	291	16.7	94.5	95.0	68.0	0.0	729.7
Spillouts	70	4.0	73.7	95.0	46.4	8.9	384.4
No spillovers	1428	81.7	78.8	49 and 57	40.0	–100.0	5645.0

Source: Based on data reported in Alston et al. (2000).
Notes: This table is based on a full sample of 292 publications reporting 1886 observations. For all characteristics, the sample excludes two extreme outliers and includes returns to research only and combines research and extension so that the maximum sample size is 1772. For the research gestation lag, the sample includes only observations with an explicit lag shape, resulting in a sample size of 790 observations. For spillovers, 25 observations were lost owing to incomplete information, resulting in a sample size of 1747 observations. Some estimates have spillover effects in both directions.

evaluated, the industry to which it applied, or the evaluation methodology, because the signal-to-noise ratio was too low. Nevertheless, a predominant and persistent finding across the studies was that the rate of return was quite large. The main mass of the distribution of internal rates of return reported in the literature is between 20% and 80% per annum.

Alston et al. (2000) concluded that the evidence suggests that agricultural R&D has paid off handsomely for society, but they raised a number of concerns about the methods used in the studies that were likely to have led to upward biases in the estimates. In particular, they suggested that the studies may have suffered from bias associated with (a) using research lag distributions that were too short (the results showed that increasing the research lag length resulted in smaller rates of return, as theory would predict), (b) "cherry picking" bias in which only the most successful research investments were evaluated, (c) attribution biases associated with failing to account for the spillover roles of other private and public research agencies, in other states or other countries, in contributing to the measured benefits, or (d) other aspects of the evaluation methods used.

7.6. Recent evidence on US agricultural R&D

More recently, Alston et al. (2010) conducted a study of public US agricultural research and productivity using state-level data for the period 1949–2002. In this study the authors paid careful attention to modeling the research lag distribution and the state-to-state spillovers of research impacts, and the other types of methodological issues raised by Alston et al. (2000). They found support for relatively long research lags (an overall lag length of 50 years with a peak impact at 24 years but with most of the impact exhausted within 40 years), with a very substantial share of a state's productivity growth attributable to research conducted by other states and the federal government. These results mean that the national benefits from a state's research investment substantially exceed the own-state benefits, adding to the sources of market failure in agricultural R&D since state governments might be expected rationally to ignore the spillover benefits to other states.

Table 3 summarizes the results from the authors' preferred model, showing the distribution of own-state and national benefits from state-specific and federal investments in agricultural research and extension in the United States, expressed in terms of benefit–cost ratios and internal rates of return.[57]

Table 3
Benefit–cost ratios and internal rates of return for US agricultural R&D

	Benefit–cost ratio (3% real discount rate)		Internal rate of return	
Returns to *State R&E*	Own-state	National	Own-state	National
	Ratio		Percent per year	
48 states				
Average	21.0	32.1	18.9	22.7
Minimum	2.4	9.9	7.4	15.3
Maximum	57.8	69.2	27.6	29.1
Selected states				
California	33.3	43.4	24.1	26.1
Minnesota	40.6	55.4	24.7	27.3
Wyoming	12.7	23.6	16.8	20.9
Regions				
Pacific	21.8	32.9	20.2	23.5
Mountain	20.0	31.6	19.0	22.7
N Plains	42.4	54.5	24.9	27.0
S Plains	20.2	31.0	19.5	22.7
Central	33.7	46.8	23.1	25.9
Southeast	15.1	26.7	17.6	22.0
Northeast	9.4	18.4	14.0	19.0
USDA Research		17.5		18.7

Source: Alston et al. (2010).

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[57] We prefer to report benefit–cost ratios rather than internal rates of return, for several reasons, as discussed by Alston et al. (2010). We report internal rates of return to facilitate comparisons with other studies.

The results show that marginal investments in agricultural research and extension (R&E) by the 48 contiguous US states generated own-state benefits of between \$2 and \$58 per dollar, averaging \$21 across the states (the lower benefit–cost ratios were generally for the states with smaller and shrinking agricultural sectors, especially in New England). Allowing for the spillover benefits into other states, state-specific agricultural research and investments generated national benefits of between \$10 and \$70 per dollar, averaging \$32 across the states. The marginal benefit–cost ratio for USDA intramural research was comparable, at \$18 per dollar.

The benefit–cost ratios in Table 3 are generally large, and might seem implausibly large to some readers. In fact, however, these ratios are consistent with internal rates of return at the smaller end of the range compared with the general results in the literature and summarized in Table 2, and as discussed by others (e.g., Evenson, 2002; Fuglie and Heisey, 2007). Specifically the estimates of own-state "private" rates of return ranged from 7.4% to 27.6%, with an average of 18.9% per annum across the states and the estimates of national "social" rates of return ranged from 15.3% to 29.1%, with an average of 29.1% per annum across the states, and the rate of return to USDA intramural research was 18.7% per annum.

8. Conclusion

Innovation in agriculture has played an important role in the long history of the world and in the transition from poor hunter-gatherer societies to modern industrial economies, processes that are continuing today. Even now, two-fifths of the people in the world depend directly on agriculture for their livelihoods; everyone who consumes food is affected by agricultural innovations. Agriculture represented an even larger share of the economy when economists began to study the economics of industrial innovation, and naturally was one of the industries studied from the outset. Hence, the economics of agricultural innovation has been an element from the outset in the literature on the economics of innovation, and at times was at the leading edge.

The literature on the economics of innovation in agriculture and the literature on the economics of industrial innovation more generally have diverged significantly, especially over the past 20 years or so. Partly this reflects the very different industrial structure of agriculture and the particular role played by the government, which may imply different types of economic questions. One point we have emphasized in our own work on agriculture and in this chapter in particular is the nature and length of the lags between research spending and its impacts on productivity. The industrial R&D literature almost universally uses a geometric lag distribution model with a high rate of depreciation (often 15%), which is certainly unsuitable for representing agricultural R&D lags.

Innovation in agriculture has many similarities but some important differences from innovation elsewhere, and we have highlighted in particular (a) the atomistic nature of agricultural production, (b) the spatial specificity of agricultural technologies and the implications for spatial spillovers and the demand for adaptive research, and (c) the role of coevolving pests and diseases and changing weather and climate giving rise to demands for maintenance research and other innovations that reduce the susceptibility of agricultural production to these uncontrolled factors. These features mean that the nature and extent of market failure in the provision of agricultural research and innovation differs from its counterparts in other parts of the economy. Consequently, different types of government policies are implied, including different types of IP protection and different roles of the government in funding and performing research.

The extensive government intervention notwithstanding, the evidence suggests that the world is continuing to invest too little in agricultural R&D—rates of return are very high. Moreover, in spite of the evidence about the payoffs, we have seen a slowdown in the rate of growth of public support for agricultural research, especially in the more-developed countries of the world, and a diversion of the research resources away from farm-productivity enhancement toward other issues of greater current political importance—such as food safety, the environment, human health (e.g., obesity), food security, and the like.

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