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RESEARCH LAGS REVISITED:
CONCEPTS AND EVIDENCE FROM U.S. AGRICULTURE

by

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ABSTRACT

Many researchers and commentators underestimate the length and importance of the time lags between initial research investment and ultimate impacts on the development and adoption of technological innovations. In both econometric studies of productivity and ex post and ex ante benefit-cost evaluations of research investments, researchers typically impose untested assumptions about the R&D lag, which can have profound implications for the results. In this paper we present a range of evidence on agricultural R&D lags including both aggregative analysis of U.S. agricultural productivity using time series data, and some specific details on the timelines for the research, development, and adoption processes for particular mechanical and biological innovations in U.S. agriculture. The aggregative analysis makes use of a comparatively rich state-level data set on U.S. agriculture that makes it possible to test hypotheses about the R&D lag and to evaluate the implications for the specification of models of production and for findings regarding the rate of return to public research investments. The results support the use of a longer lag with a different shape than is typically imposed in studies of industrial R&D. These findings are supported by the timelines for specific technological innovations, including new crop varieties, as well as tractors and other mechanical innovations.

Research Lags Revisited: Concepts and Evidence from U.S. Agriculture

1. Introduction

Many researchers underestimate the time lags between initial research investment and ultimate economic impacts. Research takes a long time to affect production, and then it affects production for a long time. The dynamic structure linking research spending and productivity involves a confluence of processes—including the creation and destruction of knowledge stocks and the adoption and disadoption of innovations over space and time—each of which has its own complex dynamics. 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. It makes the creation of knowledge unlike other production processes.

It is difficult to have precise views about the nature of the lag relationship between research investments and aggregate 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 a maximum, and, eventually, declining weights as the impact of past research investments on current productivity fades into unimportance. In practice, researchers typically define a simple ad hoc model, directly linking production or productivity to a finite distributed lag of past research investments, without reference to any formal theory. And they usually impose untested assumptions about the length and shape of the R&D lag, which can have profound implications for the results. Some such assumptions are inevitable. Thirty years ago, Zvi Griliches suggested that

> "… it is probably best *to assume* a functional form for the lag distribution on the basis of prior knowledge and general considerations and not to expect the data to answer such fine questions. That is, a 'solution' to the multicollinearity problem is a moderation of our demands on the data—our desires have to be kept within the bounds of our means." (Griliches 1979, p. 106, emphasis in original).

At issue is whether the specific assumptions that have been imposed were a cause of significant distortion in the findings.

In this paper we use comparatively rich and detailed data on U.S. agriculture to test hypotheses about the R&D lag and to evaluate the implications for models of productivity and for findings regarding the returns to public research investments. To set the scene we present a summary overview of innovation in agriculture, with particular emphasis on the United States during the 20th century. We review changes in agriculture and the role of public research institutions designed to foster agricultural innovation. Then we discuss conceptual models of innovation lags and the creation of knowledge stocks, and present an overview of evidence from the literature about the length and form of the R&D lag and the consequences of typical assumptions for findings. Against this background we present new empirical results on U.S. agriculture. First, we summarize results from a study modeling state-level changes in U.S. agricultural productivity during the period 1949-2002 as a function of U.S. federal and state government expenditures on agricultural research and extension since 1890. Then we present details on the adoption and disadoption processes for particular crop varieties and mechanical innovations. We find support for a much longer lag with a different shape than is typically imposed, a result that is pertinent to studies of industrial R&D generally, not just agricultural R&D.

2. Research and Innovation in U.S. Agriculture

Innovation in agriculture has many features in common with innovation more generally, but also some important differences. 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 means that the attenuation

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of incentives to innovate is more pronounced than in other industries that are more concentrated in their industrial structure. 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. The site-specific aspect circumscribes the potential for knowledge spillovers and the associated market failures that are exacerbated by the small-scale, competitive, atomistic industrial structure of agriculture.

Agriculture is further distinguished by the biological and spatial nature of its production technology. Agricultural production takes up a lot of space—indeed, about 40 percent 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 innovations that are often very site-specific. 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 factors such as weather and pests that are difficult or costly to control. The agricultural production consequences of pests and weather themselves vary in uncontrolled and unpredictable ways, not only within a season but systematically over time and space. Climate change implies a demand for innovation, and the co-evolution and adaptation of pests and diseases means maintenance research is required to prevent yields from declining. 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 co-evolve.

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.[1] Organized research has been an element of public policy for less than 200 years, and scientifically bred crop varieties (and livestock breeds) and their associated agricultural management practices have a history of barely 100 years. At the beginning of the 20th century a number of important general changes in science contributed to the scientific revolution in agriculture. In particular, the laws of heredity were revealed along with improvements in our understanding of the role soil fertility plays in plant growth, and an appreciation began to develop of how to better manage agricultural production systems and deal with crop and livestock diseases, drawing on the emerging disciplines of bacteriology, virology and related microbiological sciences. By introducing the results of scientific research into agriculture, agricultural scientists helped the growth in agricultural productivity and production to accelerate, particularly after the mid-1900s.

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.[2] The public sector role developed mainly over the past 100 years.[3] 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

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[1] Smith (1995) describes the origins of agriculture, beginning with the domestication of plants and animals in the fertile crescent, parts of Asia, and Meso-America about 10,000 years ago.

[2] The measures of research spending and productivity discussed here and shown in Figure 1 are described and documented in detail by Alston, Anderson, James, and Pardey (2009), 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).

[3] 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 percent 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).

enterprise had grown to $4.62 billion, an annual rate of growth of 7.1 percent in nominal terms and 3.8 percent in real (i.e., inflation adjusted) terms (Figure 1, Panel a).[4] Intramural USDA and state agricultural experiment station (SAES) research accounted for roughly equal shares of public research spending until the late 1930s, after which the SAES share grew to 69 percent of total public spending on agricultural R&D by 2006. 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 percent per annum (2.8 percent in inflation-adjusted terms) to reach $1.76 billion by 2006.

[**Figure 1**. *U.S. Agricultural R&D Expenditures and Productivity Trends, 1890-2006*]

Since 1956, spending on total public agricultural research grew on average by 7.05 percent per year (2.23 percent in inflation-adjusted terms), slower than the corresponding rate of growth of private research 7.54 percent per year in nominal terms (2.72 percent per year in inflation-adjusted terms). This means the public-sector share of total agricultural R&D drifted slightly downwards 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 state agricultural experiment stations (SAESs) plus the private sector— cost an estimated $9.2 billion, just 2.7 percent of the total spending on all areas of R&D in the United States in that year (Figure 1, Panel a).

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[4] 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, documented by Pardey and Andersen (2009). To reflect the opportunity cost of that spending one might alternatively deflate by a general price index such as the price deflator for GDP.

Long-Run Productivity Patterns

The lower panel of Figure 1 shows trends in measures of partial and multifactor productivity for U.S. agriculture. The 140 years can be seen as two distinct sub-periods of roughly equal length. Average yields of major food crops (notably corn and wheat) grew comparatively slowly from 1866 through 1935, and so did multifactor productivity (MFP), from 1880 through 1935. In the second sub-period, from 1936 through 2002, MFP grew at an annual average rate of 1.87 percent. Yields of rice and especially corn grew even faster, but wheat yields grew less quickly. Rice yields, which had grown at a rate of 1.60 percent per year from 1895 through 1935, grew at the slightly lower rate of 1.55 percent per year from 1936 through 2005; corn yields changed little, growing by only 0.01 percent per year from 1866 through 1935, but increased by 3.01 percent per year from 1936 through 2005; wheat yields grew 0.15 percent per year from 1866 through 1935 and 1.72 percent per year from 1936 through 2005. Consequently, over the period 1935 through 2002, MFP grew by a factor of 4.2, but rice yields by a factor of 3.0, corn yields by a factor of 5.3, and wheat yields by a factor of 2.9.[5]

As documented in some detail by Olmstead and Rhode (2008), biological innovation is required to sustain average yields in the face of evolving pests and diseases or to adapt to new environments as the location of production shifts, such that it would be a mistake to interpret the early period as one without innovation. But there can be little doubt that the pace of innovation accelerated in the second half of the period, and at least some of this accelerated growth must be attributed to the cumulative effects on the evolving stocks of knowledge resulting from the growth in public and private agricultural research spending that began somewhat earlier (Figure 1, Panel a). Moreover, towards the end of the period we can see some indications of a slowdown

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[5] Alston, Beddow and Pardey (2008) show that the growth in U.S, yields of the principal grain crops after 1950 had two distinct phases, with evidence of a marked slowdown in rates of yield growth during the period 1990-2008 compared with the period 1950-1989.

in the rate of growth of MFP and wheat yields, which might have been driven by a slowdown in research spending growth beginning in the middle 1970s. Until we have a more complete understanding of agricultural R&D lag relationship, research spillovers, and other elements of the attribution problem we cannot make more precise statements about the linkages between the big changes we have seen in public research spending and in agricultural productivity patterns. The remainder of this paper presents conceptual arguments and evidence in support of a much longer research lag, with a quite different shape, than is used in much of the published work, especially in the industrial R&D literature.

3. Models of Innovation Lags and Stocks of Knowledge

Over the past 50 years agricultural economists have conducted hundreds of studies of the contributions of public agricultural research and extension to productivity growth and the broader economic performance of the U.S. agricultural sector.[6] In many of those studies, agricultural productivity was modeled as a function of a distributed lag of past research investments, representing an agricultural research knowledge stock.[7] Only a few studies have presented much in the way of formal theoretical justification for the particular lag models they employed in modeling returns to agricultural research

Alston, Norton, and Pardey (1995) sketched out a conceptual framework, subsequently elaborated by Alston, Craig, and Pardey (1998), in which agricultural production uses service

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[6] Much of this effort can be attributed to T.W. Schultz and his students and other colleagues at the University of Chicago, and those who studied under them. Significant contributors to this literature associated directly with the University of Chicago include D. Gale Johnson, Vernon Ruttan, Zvi Griliches, Robert Evenson, G. Edward Schuh, Willis Peterson, Bruce Gardner, and Wallace Huffman.

[7] A comprehensive reporting and evaluation of this literature is provided by Alston et al. (2000) and Evenson (2002). 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)."

flows from a stock of knowledge that is augmented by research (see appendix A). In this framework, a finite lag distribution relates past investments in research to current increments to the stock of knowledge, but 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. Thus, the R&D lag is infinite. As a practical matter, these effects can be modeled using a finite distributed lag that approximates the underlying infinite distributed lag, and represents the confounded effects of the lags in the knowledge creation process and the dynamics of depreciation of the knowledge stock.[8] The resulting overall lag length will be longer than that between research and the creation of knowledge alone, and longer than allowed in many studies. The research lag coefficients will represent a hybrid of the effects of research on innovations, the uptake and depreciation of knowledge and technological innovations, and the consequences of the omission of the longer lags.[9]

Evidence from the Literature on Agricultural R&D Lags

Alston and Pardey (2001) argued that the truncation of the R&D lag length in econometric models is likely to lead to larger rate-of-return estimates.[10] Table 1 summarizes the results from past econometric studies of returns to agricultural research across countries, classified according to the length and form of the research lag. Most studies have used short lags (and other restrictions on the form of the lag) and shorter lags tend to coincide with larger

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[8] 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).

[9] In such a model, as longer research lags are progressively introduced, we would expect to see both an improvement in the model in general, and an increasing resolution of the parameters as meaningful representations of the impact of past research on current net increments to knowledge.

[10] If the omission of longer lags of R&D investments represents the omission of relevant explanatory variables, and R&D investments are strongly positively correlated over time, the weights on the shorter lags will be biased upward. Calculations of the rate of return will also be biased up, so long as the effect of the higher values for short lag weights more than compensates for the imposition of zero restrictions on the longer lag weights. This is quite likely when calculations of rates of return heavily discount benefits in the distant future, as happens in the typical case when a large internal rate of return is the result of the calculation.

estimated rates of return.[11] 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. Along with lag-length

restrictions, 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.[12] Both types of restrictions can have significant effects on the empirical

assessment of research benefits. Both the direction and magnitude of the bias in estimated rates

of return to R&D from restricting the length and shape of the lag profile are empirical issues, but

we suspect the bias has been upwards. This suspicion is supported to some extent by a formal

analysis of the evidence in the literature (Alston et al. 2000) and by inspection of Table 1.

[**Table 1:** *Lag Structures and Rates of Return to Agricultural R&D*]

In many cases, especially the earlier studies, the available data did not permit using or

testing for longer R&D lags. Pardey and Craig (1989) used a free-form lag structure to model

the relationship between agricultural productivity and public-sector agricultural research, and

found "… strong evidence that the impact of research expenditures on agricultural output may

persist for as long as thirty years (p. 9)" and that "… long lags—at least thirty years—may be

necessary to capture all of the impact of research on agricultural output (p. 18)." While several

studies have followed this advice, until recently none tested how much longer than 30 years the

lag should be, nor did they consider the problem in the context of an infinite lag structure.

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[11] This table represents an updated version of Table 5 in Alston et al. (2000) who conducted a meta-analysis of 292
studies that reported a total of 1,852 estimates of rates of return to agricultural R&D.

[12] 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., Huffman and Evenson 1989, 1992, 1993, 2006; Evenson 1996). A small number of studies have used free-
form lags (e.g., Ravenscraft and Scherer 1982; Pardey and Craig 1989; Chavas and Cox 1992).

However, in a recent application using long-run, state-specific data on U.S. agriculture (summarized in section 4), Alston, Anderson, James, and Pardey (2009), hereafter AAJP (2009), did test for longer lags, and found in favor of a gamma lag distribution model with a much longer research lag than most previous studies used—a research lag of at least 35 years and up to 50 years for U.S. agricultural research, with a peak lag around year 24. [13]

R&D Lags in Models of Industrial R&D

In the more general industrial R&D literature, views about the research lag structure are often reflected in terms of assumptions about the rate of geometric depreciation of the knowledge stock (the "converse" of the overall lag length that has more often been the key parameter of the research lag in agricultural R&D studies, as discussed by Alston et al. 2000). The industrial R&D literature reports a range of estimates of geometric depreciation rates used in the creation of R&D capital stocks, but the rates are generally large, implying much shorter effective research lag lengths than found by studies of agricultural R&D that explicitly tested for lag lengths.

Adams (1990) estimated an annual depreciation rate for basic research of 0.09 to 0.13, while Nadiri and Prucha (1993) estimated a rate of 0.12 for industrial R&D. Based on this and other evidence, the Bureau of Economic Analysis, BEA (1994) used a straight-line life span that corresponds to a geometric depreciation rate of 0.11 in constructing estimates of R&D net capital stocks. This rate implies that only 10 percent of today's knowledge stock will remain in use in 20 years' time. The Bureau of Labor Statistics, BLS (1989) used a slightly smaller rate of 10 percent as its central estimate, which also implies a rapid rundown of the stock of useful knowledge. BLS (1989) also considered annual depreciation rates of 0 and 20 percent, and noted that the choice of a specific rate of depreciation had important implications for the effect of R&D

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[13] Some other recent studies, beginning from an examination of the time-series structure of the data, rather than reflection about the structural relationships, have implicitly extended the lag length and found lower rates of return (e.g., Myers and Jayne 1997).

on productivity growth. In one earlier study, Griliches (1980) considered depreciation rates of 0, 10 and 20 percent; in another (Griliches 1986), 15 percent. Coe and Helpman (1993) suggested a depreciation rate of 5 percent for research applied to business-sector R&D capital, implying a much longer-lived effective stock. Coe and Helpman are in the distinct minority with their comparatively low depreciation rate (and implied long-lived effects of research on productivity). For instance, Hall and Mairesse (1995) explored the R&D-productivity relationship using 16 years of R&D data for French manufacturing firms, for which they formed an R&D capital stock using $K_t = (1 - \delta)K_{t-1} + R_{t-1}$ and depreciation rates, δ, of 15, 25, and (implicitly) 100 percent.

The same general thinking prevails in contemporary work. Sliker (2007) summarized the methodology used to create the knowledge capital stocks reported in the 2007 version of the BLS satellite accounts for R&D.[14] The measure in the satellite accounts incorporates R&D spending by business, government and non-profit institutions, and so ostensibly represents a measure of the stock of knowledge that is appropriate for economy-wide considerations. In a companion paper Mead (2007) canvassed the economics literature related only to business and industry-specific studies as a basis for informing choices regarding the choice of R&D depreciation rates used to construct the economy-wide BLS measures, and concluded that "… the 15 percent depreciation rate for R&D capital that is commonly assumed in studies of the net return to [business] R&D capital is consistent with the empirical evidence, which seems to indicate that the range of 15-20 percent is correct for the depreciation rate of business R&D (2007, p. 5)." The five studies of industry-specific R&D reviewed by Mead reported R&D depreciation rates ranging from -11 to 52 percent.[15] The Australian Government Productivity Commission (2007)

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[14] The 2007 version of these R&D satellite accounts can be obtained on line at http://www.bea.gov/industry/index.htm#satellite. See, also, Robbins and Moylan (2007).

[15] The industry-level studies included Lev and Sougiannis (1996), Ballester, Garcia-Ayuso and Livnat (2003), Bernstein and Mamuneas (2006), Hall (2006) and Huang and Diewert (2007). In constructing their measures of stocks, the BLS put aside the Hall (2006) estimates, averaged the industry-specific depreciation rates reported in the remaining four studies, and then scaled down these mid-points "... so the recommended rates are more closely

recently published a report on *Public Support for Science and Innovation* supported by a working

paper by Shanks and Zheng (2006) that reported an extensive review of literature and new

econometric results on the relationship between business R&D and economy-wide productivity

for the Australian economy. This work was subject to considerable professional and public

scrutiny. The main model used in that study entailed an R&D capital stock with a depreciation

rate of 15 percent applied to business enterprise research and development (BERD), consistent

with the central tendency of the range of adjusted industry-specific R&D depreciation rates used

by BLS in constructing the 2007 total R&D capital stocks for the United States.

It is reasonable to presume that the BLS and Productivity Commission work is consistent

with the mainstream of views in the economics profession, and can be treated as a contemporary

benchmark. Yet these widely adopted models in the industrial research literature are

fundamentally implausible, even when applied to industrial research of the most applied and

immediate nature, but especially when applied to the more substantial research that typically

takes time. Moreover, a geometric lag model implies that research has its maximum effect on

productivity immediately in the year when the investment is made, allowing no time for the

processes of research, knowledge creation, development of technology, and adoption. Such

assumptions may be plausible when applied to an aggregate of physical capital that is at its best

and most productive at the time of purchase (e.g., see Andersen, Alston, and Pardey 2007).

However, knowledge capital takes time to create and become effective, after which it may

depreciate very slowly (and even then perhaps only because of obsolescence rather than any

physical deterioration) if at all. The implied relationship between research investments and the

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centered on a value of 15 and that the overall ranking of industry-level rates suggested by the literature is preserved (Mead 2007, p. 6)." The rationale for excluding the R&D depreciation rates reported by Hall (2006) was "…because the rates that are presented in the first portion of the [Hall] study, which are based on a production function seem unreasonably low, and the rates that are presented in the second portion of the paper, which are based on a market valuation model, seem unreasonably high (Mead2007, p. 5)." The basis for determining that these estimates were "unreasonable" was not discussed.

knowledge stock in use, and thus the effect of research on productivity, must have a very different shape than that implied by the analytically convenient but otherwise undesirable geometric depreciation model.

In addition, and possibly more important, the relevant lag between research investments and productivity impacts is likely to be much longer than those implied by the typically assumed rates of geometric depreciation. For instance, in a model with a geometric depreciation rate of 15 percent, the marginal impact of research would have declined to less than half of its initial value after five years, and less than 20 percent after ten years. Many research investments take at least five and possibly as many as ten years before they begin to have any effect on productivity. Thus, a model with a 15 percent geometric depreciation rate imposes a generally much shorter research lag structure than can be justified in view of the typical research lags likely to be found in reality, and much different timing of the research impact. The resulting estimates of model parameters and the implied elasticities of productivity with respect to research, benefit-cost ratios, and internal rates of return are likely to have been significantly distorted.

The benchmark model of industrial R&D with no research, development, and adoption lags, and relatively rapid geometric depreciation, has stood the test of time at least in the sense that it continues to be widely used. Some questions have been raised about its implications and whether they can be reconciled with the data. At least a dozen years ago, in a paper he presented at a conference in Melbourne in 1996 (subsequently published as Griliches 1996, 2001), Zvi Griliches identified a conundrum, which was recently revisited by Bronwyn Hall (2006, 2007). Paraphrasing Griliches (1996, 2001), Hall observed that "... the measurement of the depreciation of R&D assets is the central unsolved problem in the measurement of the returns to research (2007, p. 2)." The lag relationship between research and productivity is clearly at issue. Our

work suggests that the issue goes beyond the specification of the depreciation process to the specification of the processes of knowledge creation and adoption, which have been omitted altogether from the models that treat current research as an increment to the knowledge stock, which begins to depreciate immediately.

Stylized Facts about Agricultural R&D Lags

Some stylized facts about individual technological innovations offer insights into our arguments about the R&D lag structure for agriculture and, by analogy, industry more generally. Consider crop improvement research using conventional breeding techniques. Figure 2 represents the costs and benefits over time from an investment in R&D that leads to the successful development of a new variety that is adopted by some growers for a time. Costs are incurred in the early years, in the processes of research, development, and facilitating early adoption. And in some cases, "maintenance" research might be required over the life of a technology, to sustain its usefulness and use.[16]

[**Figure 2.** *A Stylized Representation of Research Benefits and Costs for Varietal Development*]

The first phase, the "research lag," takes at least several years. This phase includes experimental work in crossing parental lines, planting and growing the resulting seed in experimental trials, evaluating the results and making selections for further development. The next phase, the "development lag" takes several more years, as selected varieties are evaluated and modified prior to commercial development, and then seed is multiplied into commercial quantities for sale. For some types of technologies, such as biotech crop varieties, the

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[16] Olmstead and Rhode (2002) referred to this as the "Curse of the Red Queen" (see also Dalrymple 2004). In Lewis Carroll's *Through the Looking* Glass the Red Queen said, "It takes all the running you can do, to keep in the same place." This colorful metaphor has a parallel in naturally evolving biological systems to which the Red Queen principle was introduced by Leigh Van Halen who broached the notion in his 1973 paper titled "A New Evolutionary Law," arguing that for a species within an evolutionary system, continuing development is needed to maintain its fitness relative to the systems within which it co-evolve.

development lag phase is extended by the several years spent developing and providing information required for regulatory approval, before the technology can be released for adoption (e.g., see Kalaitzandonakes, Alston, and Bradford 2006). Even for relatively applied work, such as the development of new crop varieties, the R&D lag can be 5-10 years or longer.

During the "adoption lag" the new variety is progressively adopted and planted in larger quantities, and the net benefits progressively increase until eventually a maximum is reached. The adoption lag reflects the time it takes for individual farmers to learn about the new variety and evaluate its usefulness in their specific environments, and in many instances it reflects further time spent adapting the variety to better suit different agroecological conditions.[17] It may also reflect lags as the market beyond the farm adapts to make use of the products of the new technology. For instance, it takes time for the food processing industry and consumers to adapt to the introduction of a new product innovation such as canola (derived from rape seed that was not edible for humans). Consumer or other market resistance has dramatically slowed the industrial adoption of many significant innovations in agriculture and the food industry—e.g., pasteurization of milk, irradiation of food, chemical pesticides, and transgenic crop varieties— with implications for the shape of the R&D lag profile for those innovations. In some cases government regulation reinforces market resistance (e.g., see Just et al. 2006).

The diffusion of agricultural innovations has a uniquely spatial dimension, since the applicability of the innovation varies systematically with space, and this aspect adds to the time spent evaluating and adapting technologies for local adoption. This process of diffusion of a given innovation often can take a further 5-10 years, depending on the nature of the technology and information systems. In years past, a significant role of agricultural extension services was

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[17] Evenson and Kislev (1975) made seminal contributions to the study of the economics of innovation and adoption of agricultural technology. Subsequently, the lag to adoption was the focus of a suite of decision-theoretic models developed by economists including Pakes (1978), Lindner, Fisher and Pardey (1979) and Feder and O'Mara (1982).

to facilitate transmission of information about new farming technologies, to accelerate adoption and shorten the adoption lags. Other innovations, in terms of modern communications technologies and improvements in education of farmers, have made that traditional role of extension less important and contributed directly to shortening adoption lags. Benefits might flow indefinitely, but for stereotypical technologies, the rate of benefits will decline over time, as shown in Figure 2. Eventually, the particular variety will be disadopted by some farmers as it becomes less effective against evolving pests and diseases or is made obsolete by the development of superior varieties. But in many cases a variety may serve as breeding stock, contributing to the varieties that replace it, with vintage carryover effects. Hence, the benefit stream will continue to flow so long as the variety *or its offspring* continue to be grown by some farmers.

Combining these various elements of lags, it is easy to imagine a typical varietal technology with a research and development lag of 5-10 years, in which no benefits are earned, followed by an extended adoption phase, with peak benefits in the range of 15-25 years after the initial investment, and sustained use after the peak, with benefits extending for a further 10 years and longer. Some other types of research (for instance, genomics and proteomics) may have significantly longer lags, especially the more fundamental types of research that lead to the most important and valuable types of innovations, some of which ultimately may be built into the new varieties. When innovations are embodied in livestock breeds or perennial crops that last for many years or decades, the biological dynamics add to both the research and adoption lags; similarly when innovations are embodied in durable physical capital such as tractors or combine harvesters. Some other types of public investments, including applied research and extension, might have significantly shorter R&D lags and less-enduring impacts. When we model the effects of *aggregate* R&D spending on multifactor productivity the R&D lag profile represents

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an average of the complete range of different types of agricultural R&D and their impacts across the entire range of agriculture.

The flows of benefits represented by the R&D lag profile in Figure 2 are analogous to the flows of benefits associated with investments in a perennial crop, such as a vineyard or an orchard. Depending on the crop and variety, it may take 3-5 years after planting before a tree or vine crop begins to achieve commercial yields and a further 5-10 years before it achieves its maximum yield. Then some varieties may stay in production indefinitely (such as chestnuts or premium wine varieties), whereas others (such as almonds or oranges) have declining yields as they age and are grubbed out and replaced after 20 years or so.[18]

In contrast, the R&D lag profile used in the stereotypical study of industrial R&D, is a geometric lag as drawn in Figure 3, which is more analogous to the flow of benefits from an investment in a machine with a fairly short commercial life expectancy, such as an automobile. In this representation, benefits begin immediately with the investment and are at their maximum at that time, reflecting maximum adoption, maximum effectiveness, or both. There is no allowance for the research, development, and adoption lags. From the outset, the assumed pattern of benefits is consistent with the tail end of the process in Figure 2, in which benefits are declining because of disadoption or obsolescence. Figure 3 also includes a trapezoidal lag model from Huffman and Evenson (1993) and the gamma lag distribution model preferred by AAJP (2009). It can be seen that these lag distributions are very different from the geometric model used in applications to industrial R&D, and much more like the perennial crop yield pattern. It is not just biological factors that make the biological analogy relevant for agricultural R&D. The same analogy is relevant for general industrial R&D: it takes many years to grow and develop a

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[18] In this world, extension may be like alfalfa, which is a perennial crop that has a payoff within the first year of production but continues to yield benefits for a number of years until eventually the field is replanted with alfalfa or some other crop. Another example is strawberries, which have been drifting in the direction of being grown as an annual crop; and extension may have drifted analogously.

technology before it can begin to bear fruit, and then it may continue to bear fruit for many more years. But the standard model does not reflect these conceptions.

[**Figure 3.** *Trapezoidal, Gamma, and Geometric R&D Lag Models*]

A range of types of empirical evidence can be presented in support of the use of long R&D lags in models of agricultural innovations. In what follows we present some evidence on overall R&D lags in U.S. agriculture from aggregative models of multifactor productivity and R&D spending, as well as more-specific evidence on R&D and adoption-disadoption processes for various varietal and mechanical technologies.

4. Evidence from Models of Multifactor Productivity using State-Level Data

AAJP (2009) conducted a study linking public U.S. agricultural research investments over 1890-2002 and multifactor productivity (MFP) over 1949-2002 using state-level data for the 48 contiguous states.[19] In this study the authors paid careful attention to modeling the research lag distribution and state-to-state spillovers of research impacts. 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 35 years), with a very substantial share of a state's productivity growth attributable to research conducted by other states and the federal government (this preferred lag distribution is shown in Figure 3 as the gamma lag model). 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

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[19] The Fisher indexes of inputs, outputs, and productivity—the Andersen, Pardey, Craig, and Alston series—are revised and updated versions of indexes published by Acquaye, Alston, and Pardey (2003) and originally developed and used by Craig and Pardey (1996). They are based on disaggregated quantities of 58 categories of inputs and 74 categories of outputs. The agricultural R&D data include details on spending by individual state governments on research and extension, and by the federal government in USDA intramural labs, as well as the sources of those funds. The agricultural input, output and R&D data are more fully described and documented in AAJP (2009).

governments might be expected rationally either to ignore or to heavily discount the spillover benefits to other states.

Table 2 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.[20] The results show that marginal investments in agricultural research and extension (R&E) by the 48 contiguous U.S. states generated own-state benefits of between $2 and $58 per dollar spent on research, 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 investments generated national benefits that ranged between $10 and $70 per dollar, with an average of $32 across the states. The marginal benefit-cost ratio for USDA intramural research was comparable, at $18 per dollar.

[**Table 2**: *Benefit-Cost Ratios and Internal Rates of Return for U.S. Agricultural R&D*]

The benefit-cost ratios in Table 2 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 lower end of the range compared with the general results in the literature as reviewed by Alston et al. (2000) and summarized in Table 1, and as discussed by others (e.g., Evenson 2002; Fuglie and Heisey 2007). Specifically, in Table 2 the estimates of own-state "private" rates of return ranged from 7.4 to 27.6 percent, with an average of 18.9 percent per annum across the states. Estimates of national "social" rates of return ranged from 15.3 to 29.1 percent, with an average

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[20] We prefer to report benefit-cost ratios rather than internal rates of return, for several reasons, as discussed by AAJP (2009). We also report internal rates of return to facilitate comparisons with other studies.

of 22.7 percent across the states, while the rate of return to USDA intramural research was 18.7 percent per annum.

The plausibility of the general findings is reinforced by comparing the scale of the flows of annual benefits from productivity growth with the flows of annual research costs. AAJP (2009) partitioned agricultural output in the years from 1949 to 2002 into a part that could be attributed to conventional inputs using 1949 technology and a residual attributable to productivity growth since 1949. By 2002, productivity growth since 1949 accounted for 61 percent of the value of production, yielding a benefit worth $106.9 billion in that year alone; many times greater than the annual flow of public research spending. Using a 3 percent discount rate, the present value of productivity growth over the period 1949-2002 was worth 22.5 times the value of public research and extension spending over the period. This is a crude first approximation of the benefit-cost ratio because (a) it does not count the cost of research done before 1949 that contributed to the productivity growth during 1949-2002, (b) it does not incorporate the benefits after 2002 resulting from research done before 2002, (c) it does not measure research benefits that are not manifested through farm productivity (e.g., environmental and human health), and (d) it does not allow for the roles of private research and international spillovers. AAJP (2009) experimented with ways to allow for these aspects and the resulting approximate benefit-cost ratios remained large though somewhat smaller than those derived from their formal econometric estimation and benefit-cost analysis.

The AAJP (2009) estimates and sensitivity analyses demonstrate an important point: while the approximations inherent in their specific assessment (and, by implication, this body of literature generally) may influence the specific results, modeling assumptions are not the fundamental drivers of the general findings of high rates of return to agricultural research. The general findings are driven by the fact that the scale of the annual benefits from productivity

growth is very large relative to the scale of annual spending on agricultural R&D. AAJP (2009) also experimented in the econometric analysis by imposing different lag distributions on their model, allowing for different lag shapes and different maximum lag lengths, along with other variations in model specification. The results were mixed. In some cases shorter lags resulted in larger estimated benefit-cost ratios but, for reasons that are not yet fully understood, other modeling details were an important co-determinant of the sensitivity of results to truncating the lag length.[21]

5. Biological Innovations and Uptake in U.S. Agriculture

Olmstead and Rhode (2008) challenged the view that biological innovation in U.S. agriculture was primarily a 20th century phenomenon, and provided compelling evidence to support their position. Clearly, much of the early development of U.S. 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 co-evolving 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.[22]

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[21] The preferred model was linear in logarithms of the variables—including knowledge stocks that were linear aggregates of lagged research and extension spending. AAJP (2009) also tried a model that was linear in the levels of the variables. This linear model resulted in a significantly shorter R&D lag distribution (a peak lag at year 13 instead of year 24) and generally larger estimates of social benefit-cost ratios (albeit with a bigger share in the form of state-to-state spillovers). However, the logarithmic model dominated the linear model in terms of its statistical performance and consistency with priors.

[22] 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

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. The presentation is necessarily brief, and for the most part we abstract from the spatial dimension, which is an important inherent source of the time lags on which we focus. Drawing on Chan-Kang and Pardey (2008) 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.[23] Next we present technology (R&D) timelines and adoption curves for hybrid corn (in the mid-twentieth century) and biotech corn (in the last decade of the twentieth century), and then adoption curves for several mechanical technologies.[24]

Wheat

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. 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 characteristics (such as protein content and

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ethanol—that result in significant changes in relative prices of inputs and outputs that in turn influence adoption incentives.

[23] See, also, Olmstead and Rhode (2002).

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

milling characteristics), and the development of new breeding techniques, such as "shuttle breeding," have also been important.[25]

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 (Syme 1983). 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. The primary source of wheat semidwarfism in spring wheats was the *Norin 10* germplasm, a seed collected in Japan during the 1940s and brought to the United States by S.C. Salmon, a USDA Agricultural Research Service scientist.[26] Orville Vogel, a USDA scientist at the Washington State University's Pullman station, crossed *Norin 10* with *Brevor*, a winter-wheat line with which he had been working.[27] This U.S. cross became the foundation for semidwarf varieties developed later at CIMMYT, the International Maize and Wheat Improvement Center located in El Batan, Mexico. It was used extensively in early CIMMYT breeding to create rust-resistant, fertilizer-responsive germplasms (such as *Pitic 62* and *Sonalika*) that fueled the Green Revolution. In turn, CIMMYT varieties were subsequently introduced into the United States for

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[25] Norman Borlaug's early (pre-CIMMYT) work in Mexico was initially devoted to breeding rust-resistant lines. Following then-current breeding doctrine, he sought local breeding advances to solve local problems. 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." Borlaug's "shuttle breeding" had two outcomes. First, it reduced the time to develop and release improved varieties from about 10 years to about 5 years. Second, the procedure yielded broadly-adapted disease-resistant varieties, which could be grown in a broad range of micro-environments.

[26] Spring wheats are planted in spring and harvested in late summer or early autumn. Winter wheats are planted in late autumn, lie dormant over winter, and are harvested in the following late autumn-early summer.

[27] Dalrymple (1980) provides more details of the history. Brennan and Fox (1995) point out that *Brevor* was developed from crosses with Australian varieties so that, according to their parentage proportions, *Brevor* could be considered 3/8 Australian; *Norin 10/Brevor*, 3/16 Australian.

their dwarfing and other desirable characteristics, while further semidwarf varieties have been developed in the United States without any CIMMYT germplasm.

Rust fungi, attacking the leaves and stems of the wheat plants, have always threatened wheat yields. Since the various fungi are able to mutate, a particular control method can only work temporarily: the disease evolves in response to biological or chemical controls, and eventually reappears in a new form. Breeding has traditionally been one of the main responses to rust infestations—new varieties are developed that resist the locally-dominant rust strains, and are replaced when new rusts appear to which those varieties are not resistant. Regional variation in the characteristics of rust strains has been one of the reasons for localizing breeding work. Such localization can be understood in both a spatial and temporal sense: high wheat yields are dependent upon the existence of wheat lines that are resistant to the rusts that are dominant in a given time and place.[28]

From 1900 to 2003 a total of 1,051 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 even more 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 4, Panel a. Considering all planted wheat varieties, their (area-

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[28] In addition, different types of wheat perform differently in different locations. In the Northern Plains states (Montana, Minnesota, and the Dakotas), spring wheats are grown, including the hard (high protein) red wheats used for bread-making, and durum wheats used for pasta. In the Central Plains (Nebraska, Colorado, Iowa, and Kansas) and Southern Plains (Oklahoma and Texas), winter wheats dominate, primarily hard red and white wheats. The Northwest (Washington, Oregon, and Idaho) also grows winter wheats although these are mainly soft wheats useful for biscuits and noodles. Montana is more like the Northern Plains than the West.

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 still 12.3 years by 2003. Figure 4, Panel a also shows a similar vintage profile for rice. The area-weighted average age of all rice varieties planted since 1999 was 6.6 years (since 1956 the average age has been 9.1 years). Figure 4, Panel b decomposes the vintage profiles for wheat, and shows that the (area-weighted) average age of the oldest ten varieties in use still averaged 38.7 years for the post-1999 period (when these ten varieties were planted on only 1.04 percent of the wheat acres in the United States). The ten youngest varieties in use, accounting for just 0.71 percent of the U.S. wheat acreage after 1999, had an average age of 1.09 years. 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.

[**Figure 4:** *Wheat Varietal Vintages, 1919-2003*]

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 wheats 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 U.S. wheat acreage around the beginning of the 20th century.

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 (Figure 5). One grandparent, *Lark*, is a direct derivative of a CIMMYT line (bred by a private U.S. breeder from several CIMMYT lines). Other recent ancestors, including *Olaf*, *Chris*, and *Era*, are the products of continuing work by breeders in North Dakota and elsewhere to incorporate rust resistance into varieties suitable for spring wheat production on the Northern Plains. The pedigree is complex, and demonstrates the ability of modern wheat breeders to isolate desirable traits from a wide variety of wheat strains, and incorporate those traits into lines suitable for production in diverse environments.

[**Figure 5**: *Pedigree of the Wheat Variety, Pioneer 2375*]

Table 3 reveals that 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 pre-date 1960. Notably the variety is an agglomeration of genetic material obtained from disparate locales. Only 5.3 percent of the documented nodes involve Minnesota material; more than one-half of the genetic material had its origin outside the United States.

[**Table 3**: *Attributes of the Wheat Variety, Pioneer 2375*]

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, but with impacts clearly extending 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.

Hybrid Corn

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. Appendix Table 1 represents a timeline of key events in the development of hybrid corn. 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.

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.

The time path of the adoption process is interesting, too. 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).[29] 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 percent of its corn acreage planted to hybrids in 1936 (with 90 percent of its corn acreage so

planted just four years later), while it took until before Alabama—a state with distinctive

agroecological attributes compared with the principal Corn Belt states—had 10 percent of its

corn acreage under hybrids. This delay 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. By 1950, 80 percent 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.

[**Figure 6:** *Uptake of Biological Innovations for Corn*]

If we think of the entire research, development, and adoption process for hybrid as having

begun as late as 1918 (if not in the early 1900s with Shull and others), then the total process that

had been accomplished 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,

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[29] Dixon (1980) used additional data on the uptake of hybrid corn, beyond that reported by Griliches in 1957, to re-estimate 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)." In a recent working paper Sutch (2008) discusses the roles of synthetic fertilizer and Henry Agard Wallace as contributors to the yield and adoption of hybrid corn, respectively.

would be required to represent the links between investment in hybrid corn research and resulting impacts on aggregate agricultural productivity, though not clear just how long those lags should be nor what shape the lag distribution should assume.

Biotech Corn

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 crop varieties. Among these, corn, soybeans, cotton, and canola are the most important biotech crops.[30] 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 to 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. Timelines that summarize the long lags required to develop both these modern biotechnologies are presented in Appendix Tables 2 and 3.

Notably, 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 1997) and the Western corn root worm (first released for commercial use in 2006), among others. These have been "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

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[30] 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.

herbicide tolerance.[31] Hence, biotech corn is not a single, simple innovation. 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

U.S. corn-growing states and in the nation as a whole. Genetically engineered (GE) corn was

first planted on U.S. 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 percent of U.S. 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.[32] 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, Alston and

Bradford 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

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[31] 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 (pers. comm., September 2008).

[32] 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.

slower spatial diffusion among states that characterized hybrid corn, possibly because of improved communications and farmer education, perhaps assisted by public extension services. Thus biotech corn achieved 80 percent adoption within 13 years compared with 19 years for hybrid corn. However, other 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 to 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 to 30 years so far.[33] 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.[34]

6. Uptake of Other Innovations by U.S. Agriculture

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 20th 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 20th century; *information technologies,* involving computers, electronics, robotics, remote sensing, and geographic information systems (GIS) technologies, are mainly a relatively recent and contemporary

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[33] 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.

[34] The cumulative nature of the crop improvement process is clearly evident in the case of corn; the GE innovations of the late 20th century such as herbicide tolerance or insect resistance are themselves being bundled into hybrid corn varieties that are the progeny of an early 20th century innovation.

phenomenon, though the telephone and telegraph can be seen as earlier examples.[35] 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 U.S. farms: tractors, electrification, and

telephones.[36] Panel b, for comparison, includes the national adoption curves for hybrid corn and

GE corn (as represented in more detail in Figure 6), along with GE soybeans.

[**Figure 7:** *Uptake of Agricultural Technologies in the United States*]

In 1920 7 percent of U.S. farms had electricity. This percentage grew in a classic

sigmoid shape to over 90 percent within the following 30 years. The adoption process for

telephones was much different. The percentage of farms with telephones fell from 40 percent in

1920 to 25 percent in 1940, reflecting, perhaps, the effects of the Depression and World War II.[37]

Then from 1940 forward the number of farms with telephones grew 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 20th century; falling from 6.4 million in 1920 to 6.0 million in 1940, then

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[35] Olmstead and Rhode (2000 and 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.

[36] 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.

[37] 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, for example, 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 U.S. telephone industry during the 1930s. See also studies cited by Olmstead and Rhode (2000).

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.[38] Figure 7, Panel a shows that the adoption process extended over

50 years, from before 1920, when less than 5 percent of farms had tractors, through to the early

1970s, when the fraction of farms with tractors stabilized at almost 90 percent. 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

aggregate across different states and different agroecologies and production systems that may

have adopted tractors sooner or later, faster or slower. And it is 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.[39] 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

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[38] Olmstead and Rhode (2001) provide an insightful analysis of the adoption of tractors in U.S. 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, as determinants of the adoption decisions that were exogenous to individual farmers but endogenous to the sector as a whole.

[39] 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.

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.

In Figure 7, comparing the adoption curves for corn and soybean varieties in Panel b with those for tractors, electricity, and telephones in Panel a, 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.

7. Synthesis, Lessons, and Implications

The premise of this paper is that researchers often underestimate the length and importance of the time lags between initial research investment and ultimate impacts on the development and adoption of technological innovations. A simple conceptual model shows that in principle the R&D lag may be infinite—some innovations, such as the wheel or wheat, have been in use for a very long time and are likely to stay in use for a long time to come—even if the process of knowledge creation is relatively rapid. As a practical matter, it may be reasonable to use a finite lag to approximate the infinite lag, but it may be necessary to use a significantly longer lag than many studies have used (including more years in particular for the processes of knowledge creation and development), especially in the context of industrial R&D.

Most of our work in this paper has been directed towards presenting evidence from U.S. agriculture in the 20th century to justify our claim that R&D lags are long, and longer than those typically assumed and imposed. One form of evidence is the result of an econometric study of state-level productivity over 1949-2002 as a function of federal and state spending on agricultural R&D and extension over 1890-2002. The preferred model used a gamma lag distribution model (as depicted in Figure 3) with a peak lag at year 24. This lag distribution is reasonably consistent with the other evidence we present about research and adoption lag processes for particular technologies, especially crop varieties about which we have a lot of specific information.

In recent years the trapezoidal lag model of Huffman and Evenson (also depicted in Figure 3) has been relatively popular, and it uses a longer lag than many previous studies of agricultural R&D. Even so its overall length is shorter and with an earlier peak (between years 10 and 15) than in our preferred gamma distribution model. In practice it is difficult to discriminate econometrically between our preferred gamma distribution model and the Huffman and Evenson trapezoidal model (or, indeed other broadly similar models), unless one has strong priors about other aspects of the specification (such as functional form, the treatment of extension lags versus research lags, and state-to-state spillovers of research impacts). Moreover the main general implications of the two models are similar, so it is easy to understand how one could settle upon a model with relatively short lags, especially given the ever-binding constraints of limited data that argue for shortening lags. However, the evidence we have presented of adoption processes that last for 10-15 years, at least, after an R&D lag of perhaps 10-15 years, would suggest that the Huffman and Evenson lag distribution is probably too short and peaks too early. In particular it may be more suitable as a representation of the adoption process alone than as a representation of the combination of the R&D process and the adoption process.

One question is whether the truncation of the lag length matters. In particular contexts we can demonstrate how truncation of the lag is likely to result in larger estimates of benefit-cost ratios (or higher rates of return) to research. Over time, studies of agricultural R&D have tended to use longer lags, and perhaps as a result they have tended to find lower rates of return. However, in theory the direction of this effect is uncertain, and in practice it is confounded with other aspects of the analysis. In any event, extending the R&D lag is unlikely to change the predominant finding from such studies, which is that the measured rate of return to agricultural R&D is very high—perhaps implausibly so—even if it may affect the estimate somewhat.

In some other settings the propensity for economists to underestimate R&D lags may have more important implications. Over the past 10-15 years we have seen early warnings of a slowdown in the rate of agricultural productivity growth in the United States, and in some other countries. This slowdown may reflect an earlier slowdown in the rate of growth of agricultural research expenditure and a redirection of expenditure away from productivity enhancing research. The consequences may be severe given expectations of global population growth and the implied growth in demand for food, in conjunction with a shrinking natural resource base and the diversion of the existing resources to produce energy crops for biofuels. To meet these requirements agricultural productivity may have to grow even faster in the 21st century than in the 20th century, which means more than doubling recent rates. If the R&D lags are short it is possible to correct course and recover in reasonable time: resources could be redirected into R&D to accelerate productivity growth in time to meet requirements. But if the lags are as long as we suggest, the main productivity slowing effects of past policy decisions may not yet have been revealed, and even an immediate reform of R&D policy, valuable though that seems likely to be, might not have much impact before the middle decades of the century.

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Appendix A: A Conceptual Model Linking Research and Productivity

We begin with a production function in which output, Q_t, is a function of a vector of conventional inputs, $\mathbf{X}_t$, the stock of useful knowledge, K_t, a vector of nonmarket inputs, $\mathbf{Z}_t$, such as weather, and purely random elements, u_t.

(1) $Q_t = \mathrm{f}(\mathbf{X}_t, K_t, \mathbf{Z}_t, u_t)$

Assuming the production function is separable in these variables and characterized by constant returns to scale, it may be expressed, alternatively, as a productivity function:

(2) $MFP_t = \dfrac{Q_t}{X_t} = \mathrm{g}\left(K_t, \mathbf{Z}_t, u_t\right)$

where MFP_t is a multifactor productivity index and X_t is an input quantity index.

The dynamics of the stock of useful knowledge is at the heart of empirical models used to explore the rate of return to research, if only implicitly. In our conceptual framework, we want to distinguish between the creation and depreciation of knowledge. The stock of knowledge increases as new ideas or innovations are added to the old stock through the research process. In addition, the stock of useful knowledge may depreciate over time. Hence, the net increment to the stock of useful knowledge is equal to the difference between current innovations (gross increments, I_t), and current depreciation (gross decrements, D_t), to the stock of useful knowledge. That is

(3) $K_t = K_{t-1} + I_t - D_t$

We take innovations, I_t in the current year to be a function of research investments, R, in the current year and up to L_I past years

(4) $I_t = \mathrm{i}\left(R_t, R_{t-1}, R_{t-2}, ..., R_{t-L_I}\right)$

Here, the research variable is general, without any distinction between public and private, or basic and applied, research and extension.

How the stock of knowledge, itself, evolves has been given different interpretations in the literature. If all knowledge were fungible and non-depreciable, the aggregate stock of knowledge would evolve according to

(5) $K_t = K_{t-1} + I_t = \displaystyle\sum_{s=0}^{\infty} I_{t-s}$

Implicit in (5) is the idea that increments to knowledge in the past, that were caused by research in the very distant past, are just as effective today as the most recent innovations. Knowledge grows unidirectionally, and utilization does not vary according to the vintage of the innovations. Fulginiti and Perrin (1993) used this model, which, combined with (4) implies an infinite research lag.

Most studies, however, have used specifications in which the effects of research on productivity decline over time, perhaps to zero. For most of us it is reasonable to presume that, in general, current production is affected more by recent innovations than by innovations in the very distant past. A practical solution is to treat the problem as if knowledge depreciates, and we consider two alternative representations of the depreciation process. First, suppose we take gross decrements to the current stock of useful knowledge, like gross increments, to be a function of research investments in the current year and up to L_D past years.

(6) $D_t = \mathrm{d}\left(R_t, R_{t-1}, R_{t-2}, ..., R_{t-L_D}\right)$

Then, combining (4) and (6), the net increment to the stock of knowledge, $N_t = I_t - D_t$ is a function of research investments in the current year and up to L_N past years (L_N is the greater of L_I and L_D).

(7) $N_t = I_t - D_t = \mathrm{n}\left(R_t, R_{t-1}, R_{t-2}, ..., R_{t-L_N}\right)$

Now the aggregate stock of knowledge is a function of all past net increments to knowledge, but since the net increment might (at least in principle) be negative the knowledge stock need not grow unidirectionally, and different vintages might effectively depreciate at different rates. The aggregate stock of knowledge would evolve as

(8) $K_t = K_{t-1} + N_t = \sum_{s=0}^{\infty} N_{t-s}$

Equation (5) can be seen as a special case of equation (8) with no knowledge depreciation, and hence where net increments to knowledge are the same as gross increments. In either case, it can be seen that the unobservable stock of knowledge is equal to the sum of all past net increments to knowledge, and thus it depends on all past research investments.

Alternatively, in the spirit of Jorgenson's (1973) argument for an aggregate physical capital stock, and as suggested by Griliches (1980, 1986), a proportional declining balance or geometric depreciation rule may be used to represent changes in an aggregate stock of knowledge. Using δ to denote the depreciation rate, the aggregate stock of knowledge would evolve over time according to

(9) $K_t = (1-\delta)K_{t-1} + I_t = \sum_{s=0}^{\infty}(1-\delta)^s I_{t-s}$

The industrial R&D literature uses this formulation, or variants thereof, and either imposes or reports a range of estimates of geometric depreciation rates for R&D capital stocks. In addition, , however, the "benchmark" model assumes $I_t = R_t$, which can be seen as a special case of equation (4) such that the current gross increment to knowledge is equal to the current research expenditure, without any allowance for the years spent in the processes of knowledge creation, technology development, and diffusion of innovations. Hence,

(10) $K_t = (1-\delta)K_{t-1} + R_t$

This formulation is analytically and empirically convenient, but almost surely misspecified in terms of both the length and shape of the R&D-productivity lag relationship.

The agricultural R&D literature generally has not dealt with knowledge stocks and their depreciation as explicitly and, perhaps fortuitously, may have avoided some of the problems associated with this formulation.[40] Even so, in many cases the agricultural R&D lag distributions probably have been misspecified partly because the authors have not worked through a framework such as that presented in this appendix.

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[40] Around two-thirds of the empirical studies linking private R&D expenditures to productivity summarized in tables 1, 2 and 3 of CBO (2005), use firm-specific R&D and productivity data. Schankerman (1981) identified a potential double-counting problem, wherein the labor, capital, and other input costs of the firm may already include the labor, capital, and other costs also reported as private R&D expenditures. In the agricultural R&D literature, typically aggregate measures of farm productivity are linked to measures of research conducted by public agencies; by construction avoiding the double counting problem that can plague the firm-specific data typically used to assess the productivity consequences of industrial R&D.

Figure 1. *U.S. agricultural R&D expenditures and productivity trends, 1890-2006*

Panel a. Public, private, and total agricultural R&D spending, 1890 – 2006
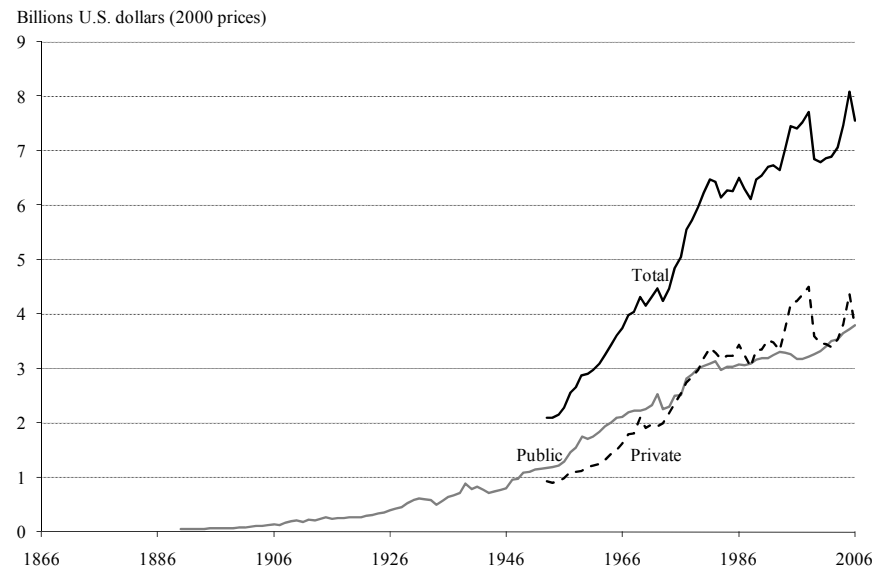
Panel b. Multi-factor productivity and average U.S. yields for selected crops
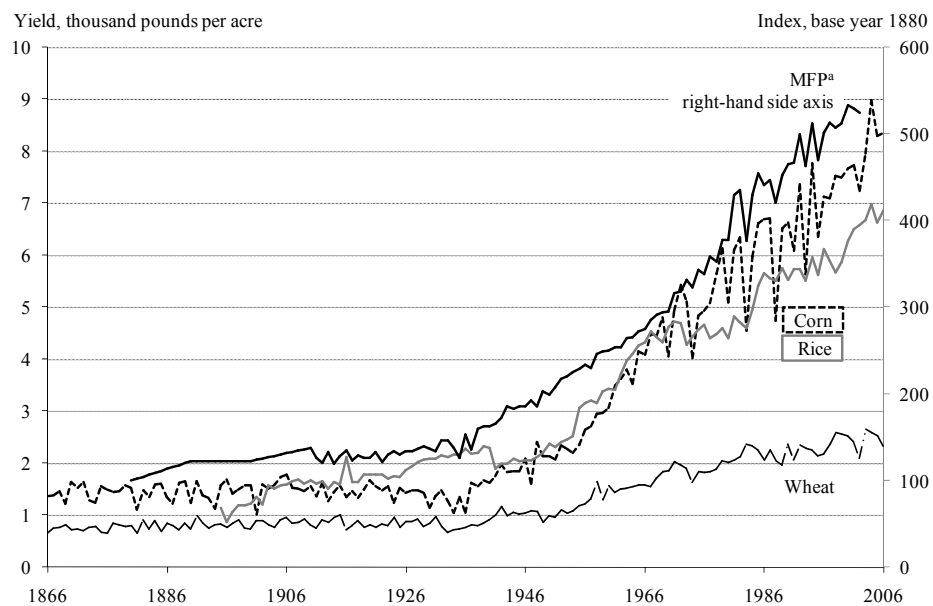
Source: Panel a: Alston et al. (2008) and Dehmer and Pardey (forthcoming). Panel b: Alston et al. (2008).

Notes: Public agricultural R&D spending represents the sum of total SAES and USDA intramural spending. Nominal expenditures were deflated to year 2000 prices using an U.S. agricultural research price deflator reported in Pardey and Andersen (2008).

Figure 2. *Stylized representation of research benefits and costs*

Gross annual benefits (dollars per year)
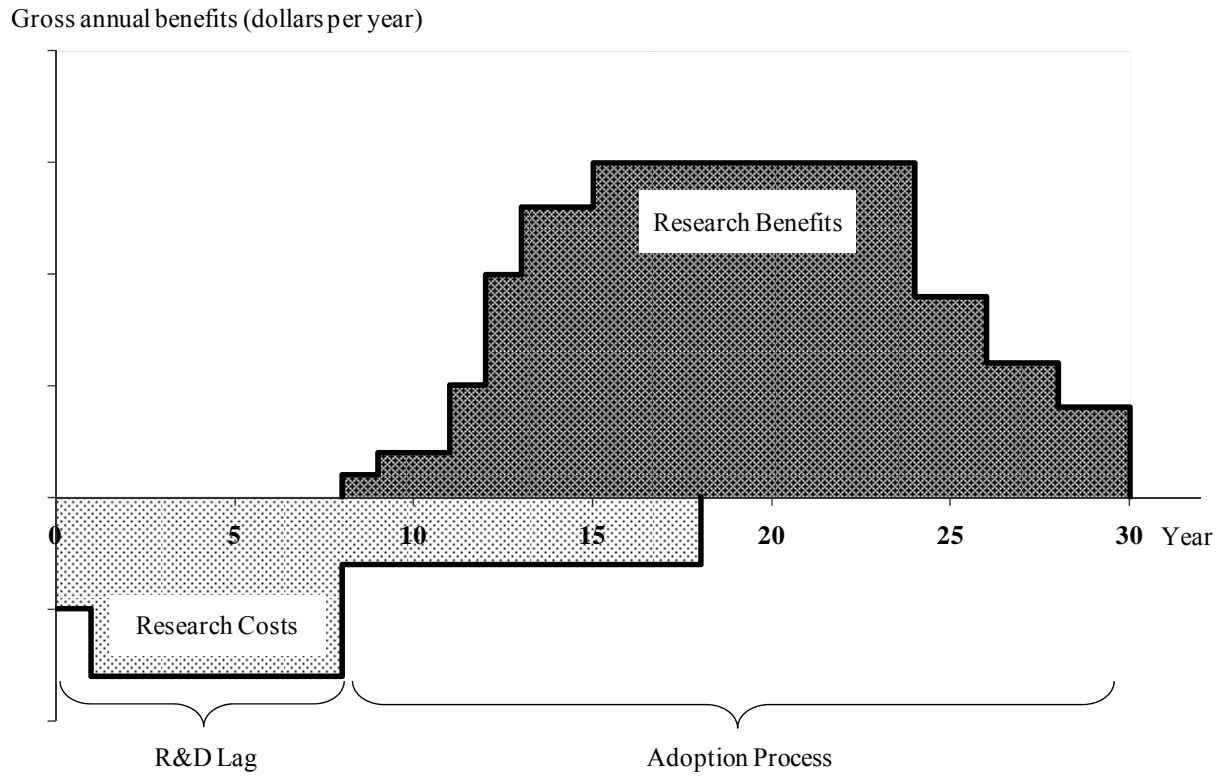
Source: Developed by the authors.

Figure 3. *Trapezoidal, gamma, and geometric R&D lag models*

Weight

- - - - Trapezoid
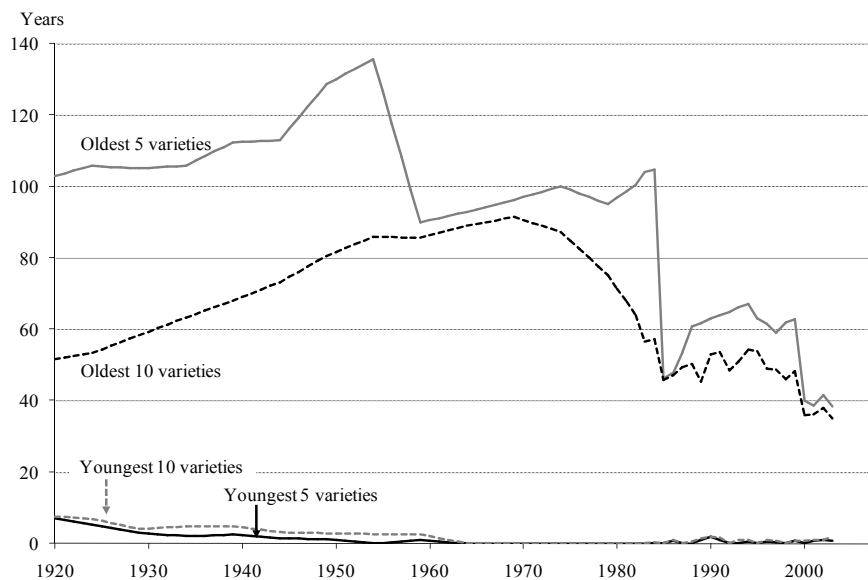―― Gamma
━━ Geometric (15% depreciation)
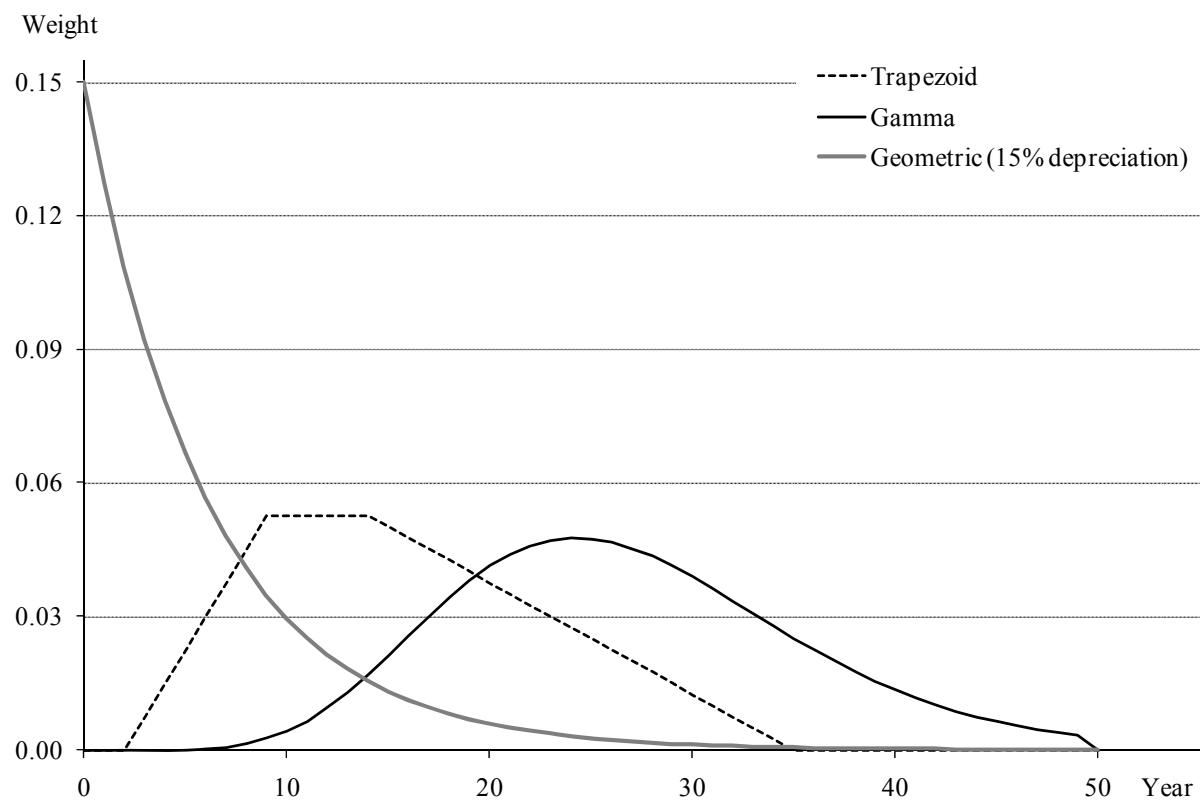
Source: Developed by the authors.

Figure 4. *Wheat varietal vintages, 1919-2003*

Panel a. Average age of U.S. wheat and rice varieties
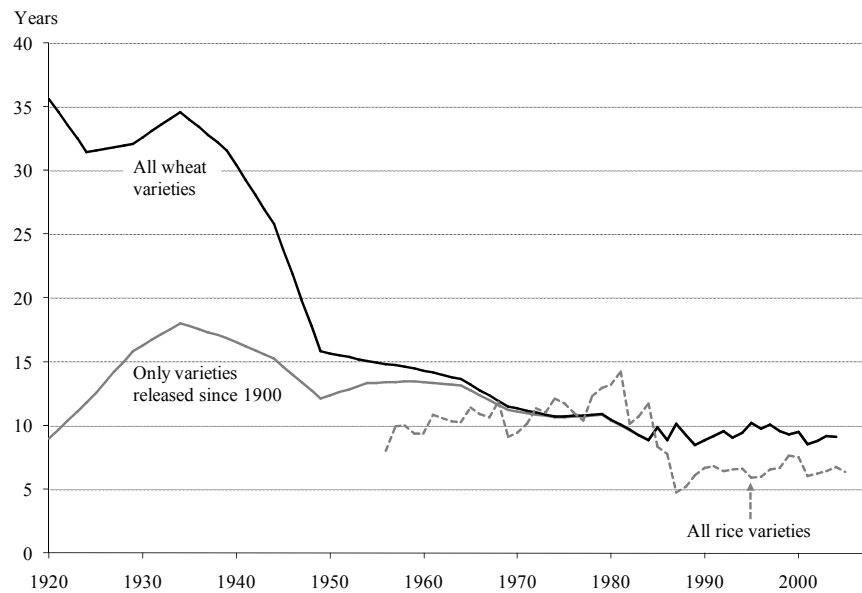
Panel b. Average age of 5 and 10 oldest and youngest wheat varieties in the U.S.

Source: Chan-Kang and Pardey (forthcoming).

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 in Panel a, we weighted the varietal age by their respective area share for each year. In Panel b, the estimates represent the average age of the oldest 5 or 10 varieties and youngest 5 or 10 varieties in each year, so the pool of varieties in each group changes over time.

Figure 5. *Wheat variety pedigree for Pioneer 2375*

Source: Chan-Kang and Pardey (forthcoming).

Notes: The first level up from the bottom of the pedigree represents the parents of *Pioneer 2375*, the second level up the grandparents, and so on. Dates refer to the year of release. Location is the point of development or discovery of each node in the pedigree. A black node represents the progeny of a varietal cross. For example, the first black node to the right of the Olaf is a cross between the two varieties *Era* and *Suqamuxi68*.

Figure 6. *Uptake of biological technologies for corn*

Panel a. Share of corn acreage planted with hybrids
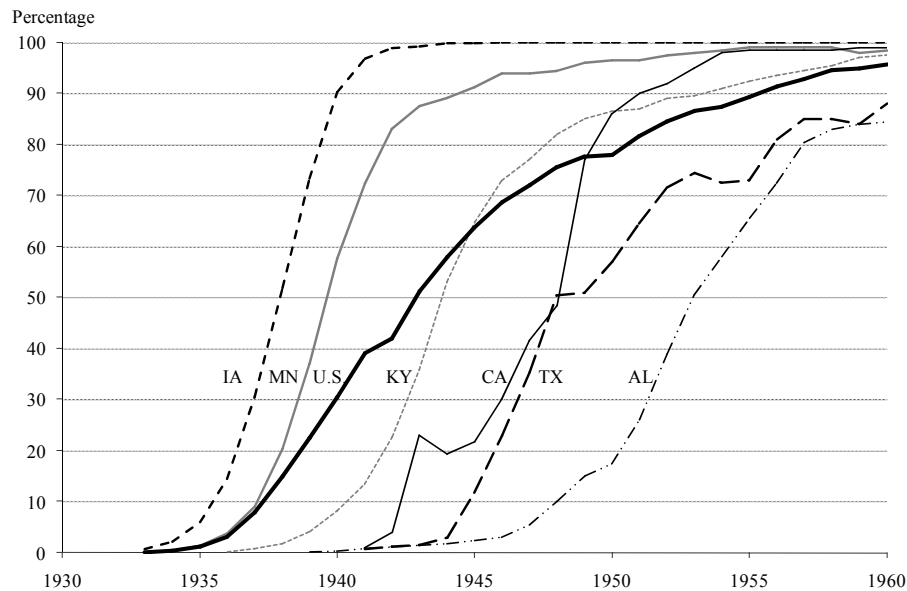
Panel b. Share of corn acreage planted with genetically engineered varieties
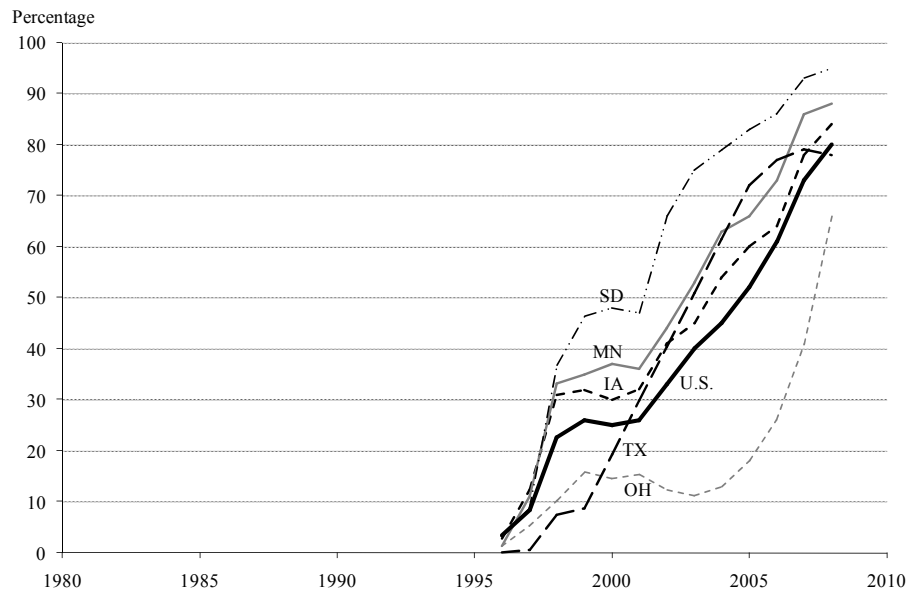
Source: Panel a: Area shares of hybrid corn obtained from *USDA Agricultural Statistics* (various years). Panel b: Genetically engineered varieties data calculated by authors from confidential data from Doane for the pre-2000 period and USDA-ERS data on biotech crops (http://www.ers.usda.gov/Data/BiotechCrops/) 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.

Figure 7. *Uptake of agricultural technologies in the United States*

Panel a. Share of farms using tractors, electricity, and telephones
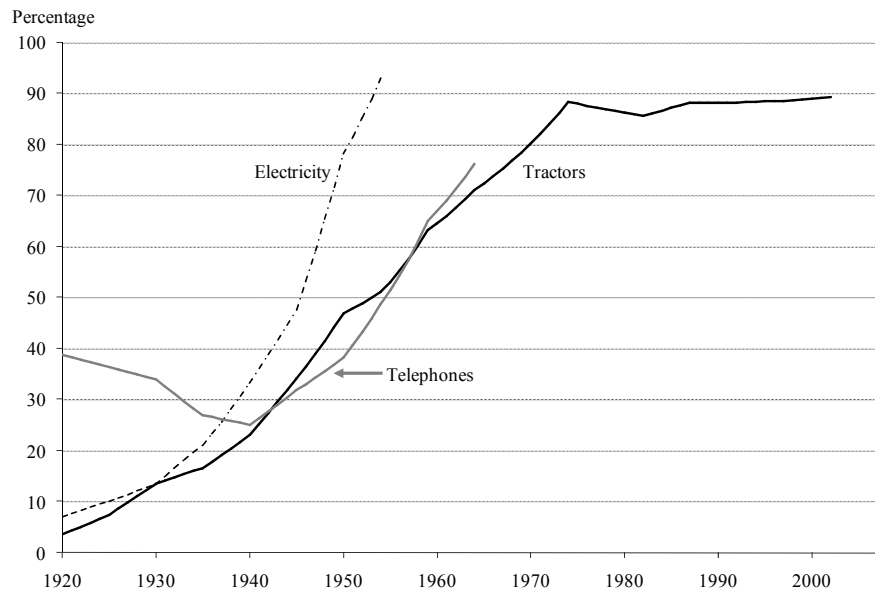
Panel b. Share of acreage planted to different types of corn and soybean varieties
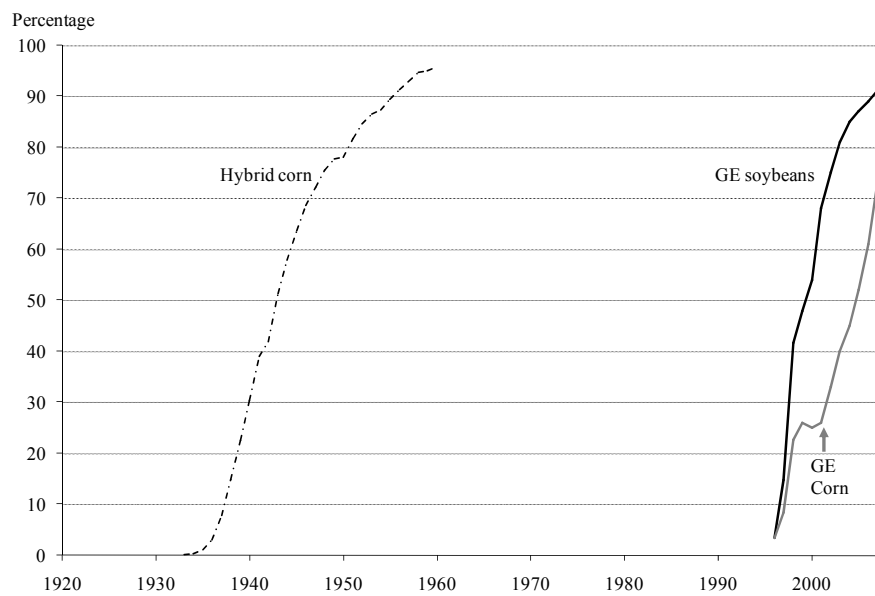
Source: Panel a: Developed by authors from U.S. Agricultural Census (various years), Panel b: see Figure 6 sources.

Notes: The plots in Panel a 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. See notes to Figure 6 for details on Panel b data.

Table 1. *Lag structures and rates of return to agricultural R&D*

Characteristic	Estimates		Rate of Return				
	Number	**Share of Total**	**Mean**	**Mode**	**Median**	**Minimum**	**Maximum**
	count		*percentage*				
Research lag length							
0 to 10	370	20.9	90.7	58.0	56.0	-56.6	1,219.0
11 to 20	490	27.7	58.5	49.0	43.7	-100.0	677.0
21 to 30	358	20.2	152.4	57.0	53.9	0.0	5,645.0
31 to 40	152	8.6	64.0	40.0	41.1	0.0	384.4
40 to ∞ 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	1,219.0
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	1,219.0
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	1,428	81.7	78.8	49 and 57	40.0	-100.0	5,645.0

Source: Based on data reported in Alston et al. (2000).

Note: This table is based on a full sample of 292 publications reporting 1,886 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 1,772. 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 1,747 observations. Some estimates have spillover effects in both directions.

Table 2. *Benefit-cost ratios and internal rates of return for U.S. agricultural R&D*

Returns to	Benefit-Cost Ratio (3% real discount rate)		Internal Rate of Return	
	Own-State	National	Own-State	National
	ratio		*percent per year*	
State R&E				
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. (2008).

Table 3. *Attributes of the wheat variety, Pioneer 2375*

Characteristics	Pedigree Nodes	
	Number	Share
	(*count*)	(*percent*)
Period		
pre-1900	19	14.3
	12	9.0
1921-40	17	12.8
1941-60	16	12.0
1961-80	13	9.8
No date	56	42.1
Total	133	100
Origin		
Minnesota	7	5.3
Rest of United States	36	27.1
Rest of World	74	55.6
Unknown	16	12.0
Total	133	100

Source: Chan-Kang and Pardey (forthcoming).

Note: To construct this table the dates of release and origin of 133 unique varieties representing nodes in this pedigree were identified.

Appendix Table 1. *Hybrid Corn Technology Timeline*

Date	Notes
Circa 5000 B.C.	Date of wild corn cobs excavated by Dr. Richard MacNeish from caves in Tehuacán Valley located in southern Puebla and northern Oaxaca, Mexico. Intact corn cobs ranged in length from 19-25 mm.
1500-900 B.C.	Early Tripsacoid corn appeared in Tehuacán Valley, suggesting a corn type resulting from introgression of Tripsacum or teosinte (*Zea Mexicana*). Generally larger in size than wild corn.
1716	Cotton Mather from Massachusetts observed and was the first to document the effects of cross-pollination in corn.
1735 and 1739	James Logan of Philadelphia conducted the first published accounts of controlled pollination of corn and described the actions of wind borne pollen.
circa 1871	Charles Darwin conducted greenhouse experiments and observed hybrid vigor in corn. In his 1877 book *Effects of Cross- and Self-Fertilization in the Vegetable Kingdom* Darwin documented how inbreeding reduced vigor, crossbreeding restored it.
1877	Professor William Beal, Michigan Agricultural College (now Michigan State University), a correspondent with Charles Darwin, conducted the first controlled crosses between varieties of corn for the sole purpose of increasing yields through hybrid vigor.
1847-1893	Robert Reid, followed by his son James Reid (originally from Cincinnati but after 1946 operating form a farm near Peoria, Illinois) developed *Reid Yellow Dent*, based on progeny from a cross between a (late maturing) southern dent variety, *Gordon Hopkins* (from the Shenandoah Valley, Virginia), and an (early maturing) New England variety, *Little Yellow* (otherwise known as *Early Yellow Flint*, an 8-10 row flint style corn grown by Indians in northeastern United States for centuries). *Reid corn*, as it was known, had 10 inch ears with 18-24 straight rows of kernels per ear, and, importantly had a maturity period appropriate for central Illinois. It served as the breeding base of Eugene Funk's *Funk Yellow Dent*. These two dent corns were the basis for some of the most widely used inbreds in U.S. commercial corn production.
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 about three times over the next thirty-five years.
1902-1910	Perry G. Holden (previously of Funk Seeds, and earlier a student of William Beal), came to Iowa State College, Ames in 1902 and was instrumental in mass education of farmers that popularized *Reid Yellow Dent* corns throughout Iowa.
1905-1912	George H. Shull (a personal friend of de Vries, Correns and Tschermark), who in 1904 arrived at the Carnegie Institution's Cold Springs Harbor Laboratory in Long Island, Connecticut, conducted a series of controlled crosses with corn from which he was able to gain a correct understanding of the effects of inbreeding and cross breeding. His results were published in two papers; one in 1908, the other in 1909. The 1908 paper titled "The Composition of a Field of Maize" was a report read to the American Breeders Association in Washington, D.C. wherein Shull drew a number of conclusions: 1) an ordinary field of corn consists of a series of very complex hybrids; 2) the decline in vigor that occurs as a result of self-fertilization is due to a gradual increase in homozygosity; 3) the goal of the corn breeder should be not to find the best pure lines but rather to identify and maintain the best hybrid combinations. His 1909 paper titled "A Pure Line Method of Corn Breeding" described a single cross method of hybrid corn production in which the progeny of a single cross between two inbred lines constitute the seed corn to be used for planting on farms.

Date	Notes
1905-1909	Edward M. East, formerly at the University of Illinois where he had begun conducting inbreeding experiments to understand the causes of poor yields in repeated selections of varieties chosen for high protein, arrived at the Connecticut Agricultural Experiment Station, with one-generation of corn in-breds in hand. Working at the same time and independently of Shull, East contributed extensively to the development of the modern corn hybrid, and, arguably, deserves as much credit as Shull (see Wallace and Brown 1988, p. 108).
1910-1919	East left for Harvard in 1910 and the corn inbreeding and crossing work at Connecticut was taken over by Herbert K. Hayes in 1911. Hayes left for the University of Minnesota in 1915 (where he had a major impact on mid-western agriculture through his teaching, research and seminal publications over the subsequent three decades). He was replaced by Donald F. Jones.
1917	Jones developed the "double-cross" hybrid, wherein four inbred lines (A, B, C and D) are crossed pairwise (i.e., B x A and C x D), making two single crosses, then the two single crosses are crossed (i.e., [B x A] x [C x D]) giving a double cross, instead of simply crossing two inbred lines to create a single-cross hybrid corn variety. Given the inbreds being used at the time had poor vigor, a single cross method was an impractical basis for commercial hybrid development. The double cross method realized a more assured and cost effective supply of hybrid seed, thus paving the way for commercial hybrid seed production.
1918	F.D. Richey of the USDA discovered *Lancaster Sure Crop*, developed by Isaac Hershey, Lancaster County, Pennsylvania, and an early maturing flinty corn.
1921	M.L. Mosher, a county agent, discovered George Krug (a farmer in Wouford County, Central Illinois) and high yielding *Krug Corn*, the progeny of a Nebraska strain of *Reid Yellow Dent* corn and *Iowa Gold Mine*.
1922	Iowa Sate Experiment station began a program of corn inbreeding and Richey was largely instrumental for including *Lancaster Sure Crop* and various strains of *Reid Yellow Dent* into this breeding program.
1933	First commercial plantings of *Hybrid Iowa 939* developed by Merle Jenkins. This is the first widely adapted hybrid, performing well in Iowa, Illinois, Indiana and Ohio.
1936	Ben Duddleston of Purdue University released *Indian WF9* (Wilson Farm Row 9) developed from *Reid Yellow Dent*. In 1935 it became one part of hybrid *U.S. 13*, the first widely popular double cross hybrid.
1960	Vastly improved inbred lines resulted in an almost complete shift from double to single-cross (or modified single cross) hybrid corn within a decade. Single-cross hybrids typically lead to higher yielding hybrids then seed developed by double-cross methods.

Source: Developed by the authors based on information in Wallace and Brown (1988), Duvick (2001) and Smith, Betrán and Runge (2004).

Appendix Table 2. *Roundup Ready® Soybean Event 40-3-2 Timeline*

Date	Notes
1970	Glyphosate, an aminophosphonic analogue of the natural amino acid glycine, was shown to have herbicidal activity by John E. Franz of Monsanto Company (US Patent 4,438,511).
1975	Monsanto establishes a cell biology research program in the Agricultural Division.
1976	Roundup herbicide (Glyphosate) is commercialized by Monsanto Company in the United States.
1981	Monsanto establishes a molecular biology group and biotechnology is firmly established as Monsanto's strategic research focus.
	The development of crops insensitive to glyphosate has been ongoing since the early 1980s (Padgette et al. 1996). Specifically:
1980	Steinruecken and Amrhein show that glyphosate specifically inhibits the enzyme 5-enolpyruvyl-shikimic acid-3-phosphate synthase (EPSPS). Monsanto scientists determine that three basic mechanisms could potentially confer glyphosate tolerance in plants:

- Overexpression of EPSPS enzymes. In 1986, Shah et al. showed that overproduction of a petunia EPSPS under the control of the cauliflower mosaic virus 35S, when transferred to a *Petunia hybrida* cell line or plants, conferred resistance to Glyphosate (Shah et al. 1986) – the level of resistance was not commercial grade,

- Glyphosate insensitive EPSPS - In 1983, Comai and co-workers showed that introduction of a bacterial EPSPS with decreased affinity (herbicide insensitive) for glyphosate when into tobacco conferred glyphosate resistance (Barry et al. 1992; Comai et al. 1983; Hinchee et al. 1993),

- Glyphosate degradation enzymes -- Introduction of a glyphosate degradation gene could inactivate glyphosate (Barry et al. 1992).

The identification of glyphosate insensitive EPSPS enzymes facilitated the development of glyphosate insensitive crops. This approach was utilized for Roundup Ready soybeans, whereby a herbicide insensitive EPSPS was identified and introduced into the crop by genetic engineering techniques (Padgette et al., 1995).

Date	Notes
Late 1980s	Several genes encoding glyphosate insensitive enzymes were isolated (Barry et al. US Patent 5,633,435).
1987	The first soybean transformation using the electric discharge was achieved (publication in 1988).
1990	A glyphosate insensitive soybean line, event 40-3-2, was obtained through expression of an *Agrobacterium* EPSP synthase (CP4) from *Agrobacterium sp*. strain CP4 (Pagette, 1995). The CP4 EPSPS gene was engineered for plant expression by fusing the 5' end of the gene to a CTP sequence derived from petunia EPSPS (Shah et al. 1986; Gasser et al. 1988; della-Ciopp: et al. 1986).
1990 & 1991	In the winter of 1990 &1991 progenies from 40-3 R seed were grown in a greenhouse and evaluated for glyphosate tolerance by spray test.
1991	Glyphosate resistant seeds from individual plants were planted in confined field trials for evaluation.
1996	Monsanto commercializes Roundup Ready Soybeans.

Source: Developed for the authors by Eric Sachs and colleagues drawing on material found in Padgette et al. (1966). Comai et al. (1983), Hinchee (1993), della-Cioppa (1986), Shah et al. (1986), Gasser et al. (1988), and Barry et al. (1992). See also Monsanto Company History at http://monsanto.com/who_we_are/history.asp.

Appendix Table 3. *YieldGard® Corn Borer Technology Timeline*

Date	Notes
1901	*B. thuringiensis* discovered in Japan by Ishiwata and 1911 in Germany by Ernst Berliner.
1950s	*Bacillus thuringiensis* is used as biocontrol agent and is registered under trade names Dipel and Thuricide.
1981	Monsanto establishes molecular biology group and biotechnology is established as Monsanto's strategic research focus.
1986	Cry1Ab gene sequence published by Wabiko et al. (1986).
1986	Cry1Ab gene is cloned into root-colonizing Pseudomonas bacteria by Monsanto researchers (Obukowicz et al. 1986).
1987	Cry1Ab gene is inserted into tomato plants by Monsanto researchers (Fischoff et al. 1987).
1991	Corn transformation technology developed (Fromm et al. 1991).
1992	YieldGard insect-protected corn event MON 810 is produced by microprojectile bombardment of embryogenic corn tissue.
1993/1994	First YieldGard field trials in the United States.
1995/1996	First YieldGard field trials in the Europe and Latin America.
1996	U.S. FDA, USDA and EPA approvals obtained for YieldGard.
1997	YieldGard Corn Borer insect-protected corn is commercially introduced in United States, providing farmers with transgenic plants exhibiting insect protection against the European Corn Borer.
1998	YieldGard first "stacked" with other GM traits (i.e., herbicide tolerance) and commercially introduced.
2004	U.S. Patent 6,713,259 "Corn Event MON 810 and Compositions and Methods for Detection Thereof" issued to Monsanto based on insect-protected corn.
2008	Regulatory approvals in twenty countries; YieldGard grown on millions of acres in Argentina, Brazil, Canada, Colombia, Egypt, the European Union, Honduras, Philippines, South Africa, Uruguay and the Unites States.

Source: Developed for the authors by Eric Sachs and colleagues drawing on material found in Obukowicz et al. (1986), Wabiko et al (1986), Fischhoff et al. (1987), and Fromm et al. (1990).