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The Benefits from Agricultural Research and Development, Innovation, and Productivity Growth

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THE BENEFITS FROM AGRICULTURAL RESEARCH AND DEVELOPMENT, INNOVATION, AND PRODUCTIVITY GROWTH

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Abstract

This report contains a review of the literature on the role of agricultural research and development in fostering innovation and productivity in agriculture. The review seeks to clarify concepts and terminology used in the area, provide a critical assessment of approaches found in the literature, report main results, and draw inferences. A key finding is that the social rate of return to investments in agricultural R&D has been generally high. Specific findings differ depending on methods and modelling assumptions, particularly assumptions concerning the research lag distribution, the nature of the research-induced technological change, and the nature of the markets for the affected commodities.

***Key words*:** Agricultural R&D, innovation, agricultural productivity, productivity growth.

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The Benefits from Agricultural Research and Development, Innovation, and Productivity Growth

1. Introduction

Over the past half century or so, hundreds of studies have been published reporting measures of agricultural productivity, the effects of agricultural research and development (R&D) on agricultural innovation and productivity patterns, and the resulting social payoffs to investments in agricultural R&D. This review summarizes and interprets the main findings from that body of work. Some emphasis is placed on the implications of the different methods used by economists for their findings about research impacts.

The review draws on several recent works in which the same issues are covered more completely. Specifically, the key references include:

- a meta-analysis of studies of returns to research by Alston, Chan-Kang, Marra, Pardey and Wyatt (2000a), published in summary form by Alston, Marra, Pardey and Wyatt (2000b);
- a review of the literature on agricultural innovation by Pardey, Alston, and Ruttan (2010), published in the *Handbook of Economics of Technical Change*;
- a new book by Alston, Andersen, Pardey, and James (2010) that describes U.S. agricultural R&D and productivity, reviews concepts and measures, and reports new estimates of the returns to U.S. public agricultural R&D investments using state-level data;
- a review of the literature on the economics of agricultural R&D by Alston, Andersen, Pardey, and James (2009),published in the *Annual Review of Resource Economics*; and
- recent work on global agricultural productivity patterns by Alston, Beddow, and Pardey (2008, 2009), some of which is incorporated along with a number of country-specific studies in a new book edited by Alston, Babcock, and Pardey (2010).

The reader is referred to these items for more complete details on issues and findings, as well as a more complete listing of the studies on which this review draws.

2. Concepts, Measures and Measurement Issues

Agricultural economists have used supply and demand models of commodity markets to represent agricultural research impacts, beginning with Schultz (1953) and Griliches (1958), with important subsequent contributions by Petersen (1967), Duncan and Tisdell (1971), Duncan (1972), Akino and Hayami (1975), and Scobie (1976), among others. Such a model is explicitly used in many studies. The same model is implicit in other studies that infer a rate of return to research from the parameters of an econometric model of production (*e.g.* Evenson 1967) or use short-cut approximations to measure benefits (*e.g.* Griliches 1958).

In the standard model of research benefits, as elaborated for example in the book by Alston, Norton, and Pardey (1995), research causes the commodity supply curve to shift down and out against a stationary demand curve, giving rise to an increase in quantity produced and consumed, and a lower price. The benefits are assessed using Marshallian measures of research-induced changes in consumer surplus for consumer benefits and of research-induced changes in producer surplus for producer benefits. The total gross annual research benefits (GARB) depend primarily on the size of the (time varying) research-induced supply shift (expressed as a vertical shift by an amount equal to a proportion, k, of the initial price) and the scale of the industry to which it applies.[1] Indeed, a common approximation introduced by Griliches (1958) is $GARB = kPQ$, where P is the commodity price and Q is the annual quantity to which the supply shift applies. Other aspects of the analysis typically have second-order effects on the measures of total benefits but may have important implications for the distribution of the benefits between producers and consumers and others.[2]

Some issues in the literature relate to the methods used for measuring the primary determinant of total measured benefits, the research-induced reduction in the industry-wide unit cost of production as represented by the supply shift, k—for instance, based on adoption rates combined with changes in experimental yields or commercial yields, or on changes in total factor productivity. This aspect is often governed by the general nature of the analysis (*e.g.* evaluation of the benefits from the development of a particular varietal improvement compared with evaluation of a national agricultural research system, whether conducted *ex ante* or *ex post*) as well as the availability of data and other information.

1. As noted by Alston, Norton, and Pardey (1995, pp. 60-61), and more recently elaborated by Oehmke and Crawford (2002), the elasticity of supply can have important implications for measures of research benefits if it is used to translate an assumed horizontal shift into a vertical shift, or vice versa.

2. The distribution of the benefits between producers and consumers depends on the relative elasticities of supply and demand, the nature of the research-induced supply shift and, less importantly, on the functional forms of supply and demand (Alston, Norton, and Pardey, 1995, review these points). The nature of the research-induced supply shift has been controversial because it matters, especially for findings concerning the distribution of benefits, and is not easy to observe. Another issue is distribution of producer benefits among producers. Even if we can be assured that producers as a whole would benefit, those who do not adopt the new technology will not gain and may even be made worse off if the adoption by others leads to price reductions.

Measures of the size and distribution of research benefits will be affected by various complications that can be introduced to extend the basic model. The introduction of international trade is a straightforward elaboration of the simple model, from which we can obtain measures of welfare impacts for different spatial or market aggregates. It becomes slightly more complicated when we allow in the same model for technological spillovers. More elaborate and complex multimarket models are implied if we want to disaggregate the market structure vertically, to represent different stages of the marketing chain, or horizontally, to represent different geopolitical or spatial markets for a given product, or different products (including different qualities of the same product). Alston, Norton, and Pardey (1995) lay out the basic theory for these approaches, and a number of studies have reported specific applications.[3]

A further dimension for extensions to the basic model is to allow for departures from the case of publicly provided R&D and otherwise undistorted markets. The basic model assumes the results from research are provided for free. Models that allow for proprietary technology (*e.g.* Moschini and Lapan 1997 and others) have not been used much in the applied work to date, and very little evidence is available on the distribution of benefits from private research between technology developers and providers and others, including farmers, consumers, and agribusiness. The basic model also assumes competition in the market for the commodity and the absence of any other market distortions. Models of research benefits have been extended to incorporate various types of market distortions, including (a) those resulting from the introduction of distortions associated with government policies such as farm commodity programs or trade barriers (*e.g.* Alston, Edwards, and Freebairn 1988), including the failure to impose optimal trade taxes in the large-country case (*e.g.* Alston and Martin 1995); (b) those resulting from the exercise of market power by middlemen (*e.g.* Huang and Sexton 1996); and (c) those resulting from environmental externalities (*e.g.* Antle and Pingali 1994). A general result is that the main effect of a market distortion in this context is to change the distribution of research benefits, with comparatively small effects on the total benefits. Similar results apply to the other types of extensions to the basic model that may be introduced to allow for multiple markets or proprietary technology. As shown in the meta-analysis by Alston *et al.* (2000a), most of the studies reporting rates of return to agricultural R&D have used relatively simple concepts of benefits and have not dealt formally with any of these complications that can influence the total benefits but are more important as determinants of the distribution of benefits.

3. Examples include Mullen, Alston and Wohlgenant (1990), Freebairn (1992), Frisvold (1997), Wohglenant (1997), Davis and Espinoza (1998), Zhao *et al.* (2000), among many more.

3. Data and Related Issues

As discussed by Gardner (1992) and Griliches (1994), a lot of effort and judgment goes into the creation of "data," but in many cases users do not know as much as they should about how the "data" were made and how they should be interpreted. In particular, measures of agricultural inputs (especially capital), outputs, and productivity, are very much transformed from the raw material used to make them. Studies of the returns to agricultural R&D, involve significant further transformation of data on research investments and productivity that already had embodied in them a great deal of judgment, much of which may not be apparent to the user but can have important implications for findings from studies that use them. Limitations on the types and quantities of data that are available, combined with misunderstanding of the measures or misuses for other reasons, are likely to have contributed to weaknesses in some studies linking agricultural R&D to productivity. Some of these outcomes may be inevitable. Others may be mitigated by the application of more care in the analysis and in reporting the results.

In many countries only very limited data are available, with incomplete documentation of measures that almost surely do not correspond well to the relevant theoretical constructs. For instance, many studies use FAO data on agricultural outputs and agricultural inputs that provide only partial coverage of agricultural outputs and inputs and do not allow the construction of valid index numbers. In some countries, however, relatively good progress has been made with developing and documenting improved measures of agricultural inputs, outputs, and productivity, and agricultural research investments, as used in studies of returns to agricultural R&D. Nevertheless, issues remain, as illustrated by the case of the United States.[4] Two separate long-term endeavours, one led by Eldon Ball at the USDA-ERS and the other by Philip Pardey at the University of Minnesota have produced alternative state-level data sets that entail substantial differences in spite of essentially common purposes, the use of appropriate index number theory in each case, and similar basic information. (For details and discussion, see Acquaye, Alston, and Pardey 2002; Andersen 2005; Andersen, Alston, and Pardey 2008; Alston, Anderson, James, and Pardey 2010.)

Compared with measures of productivity and its elements, measures of investment in research (and counterpart measures of stocks of scientific knowledge) have attracted much less effort and attention in the literature. This comparative neglect could be comparatively pernicious. It takes a lot of work to develop measures of agricultural research investments. In most countries, appropriate measures of public agricultural research investments are not published in suitably long time series, in the relevant form,

4. Andersen (2005) reviewed studies of U.S. agricultural productivity patterns, and documented the evolution of approaches and results. Some of the more recent studies of U.S. agricultural productivity include Ball (1985), Evenson, Landau, and Ballou (1987), Capalbo and Vo (1988), Craig and Pardey (1990a, 1990b, and 2001), Jorgenson and Gollop (1992), Huffman and Evenson (1992, 1993), Ball (1994), Pardey, Craig, and Deininger (1994), Ahearn *et al.* (1998), Ball *et al.* (1997), Ball and Nehring (1998), Ball *et al.* (1999), Acquaye, Alston, and Pardey (2002), Alston, Andersen, James and Pardey (2010), Alston, Beddow and Pardey (2009).

by any government agency.[5] To derive the relevant measures of public research spending requires delving through various government documents and sorting out those elements from particular spending lines that are truly research and truly applied to agriculture; it requires going across places and backwards through time, dealing with changing definitions, changing reporting procedures, and inevitable omissions.

The long agricultural R&D lags mean that time-series econometric studies require many years of data on both investments in R&D and productivity. Many studies have been constrained by the lack of suitably long time series, and have resorted to estimation devices that almost surely have distorted the findings—such as imposing restrictions on the lag distribution length and shape or creating estimates of past data using crude extrapolations from the present, a data step that is not always apparent to the reader of the distilled research product. Data on private research investments have been particularly difficult to obtain, even in relatively short time series, since the information is proprietary—and even public companies are not obliged to publish the relevant information, in their annual reports, in a way that would be useful to economic researchers.[6]

4. Attribution Problems in Models of Research Impacts

As discussed by Alston and Pardey (2001), attribution problems have bedevilled studies of the effects of research on agricultural productivity. The two principal areas of difficulty are (a) in identifying the component of productivity growth that is attributable to research-induced changes in knowledge and then further attributing responsibility among alternative public and private providers of R&D (the spatial and institutional-cum-sectoral attribution problem), and (b) in identifying the research lag structure (the temporal attribution problem). Similar problems arise when the analysis is focused on a particular innovation or applied to all research undertaken by a national system, but the specifics differ as does the potential severity of the problems. Many studies assume implicitly or explicitly that all measured agricultural productivity growth is attributable to R&D (or perhaps even a particular source of R&D such as public R&D within a country). Increasingly, questions arise as to how much productivity growth might be attributable to factors other than organized R&D, including evolving weather patterns, institutional changes, or economies of size associated with changing structure of agriculture. To some extent these are open questions for further research, but in many cases it is likely that organized research has been the primary contributor to the observed productivity growth and the important issue is attribution among R&D sources.

5. Some U.S. data have been compiled by Huffman and Evenson (1993), NSF (2008), BEA as reported by Robbins and Moylan (2007), and Pardey and Andersen (2009). Guidelines for compiling such data include OECD (2002 and 2005). For international data see Pardey, Beintema, Dehmer and Wood (2006) and the Agricultural Science and Technology Indicators (ASTI) web site at http://www.asti.cgiar.org/.

6. For compilations of U.S. private sector agricultural R&D data see Huffman and Evenson (1993), Klotz, Fuglie and Pray (1995), Fuglie *et al.* (1996), Echeverría and Byerlee (2002), and Dehmer, Pardey, and Alston (2009). Some limited information is available on private sector agricultural research in other countries. See, for instance, Pardey, Beintema, Dehmer, and Wood (2006).

Spatial Aspects of the R&D Attribution Problem

Spatial attribution matters because we seek to match streams of benefits to streams of costs, and agricultural research is funded mainly by public-sector entities that are defined geopolitically. Whether they were concerned with spillovers or not, studies have imposed implicit or explicit assumptions about the spatial spillover effects of agricultural research based on geopolitical boundaries. More recently, agricultural economists have been paying increasing attention to accounting for the fact that knowledge created within a particular geopolitical entity can have impacts on technology elsewhere, with implications that may matter to both the creators of the spillouts and the recipients of the spillins (see Alston, 2002, for a review of this literature, and Alston *et al.*, 2010 for some more recent discussion focused on the United States).

Many studies have simply ignored spillovers, but beginning with Griliches (1957), some studies of adoption of individual technologies allowed for spatial spillovers among states and regions within a country.[7] Some other studies have used regression-based methods to assess the overall effects of agricultural research on productivity using more aggregate (region- or state-specific as well as national) measures of R&D. Some of these have allowed for spillover impacts, and those that did found that the spillover impacts were important. For example, Huffman and Evenson (1993) found that a sizable share (upwards of 45%) of the benefits from research conducted in U.S. State Agricultural Experiment Stations was earned as interstate spillovers. This measure was based on spatial proximity. Alston *et al.* (2010) found a similarly large share of total productivity growth in any one U.S. state was attributable to R&D conducted in other states or by the federal government. They used a measure of spillovers based on state-to-state similarity of the output mix rather than spatial proximity. The modelling decisions have been at least to some extent driven by the limitations of available data and the requirements for parsimonious models. Most studies of national systems, irrespective of the method used, have implicitly assumed spatial spillovers away—in their meta-analysis, Alston *et al.* (2000a) identified less than 20% of studies allowing for *any* spillovers. Studies that did not allow for spillovers probably have suffered from a type of specification bias.

Temporal Aspects of the R&D Attribution Problem

Research takes a long time to affect production, and then it affects production for a long time. One element of the attribution problem, then, is in identifying the specifics of the dynamic structure linking research spending, knowledge stocks, and productivity. A large number of previous studies have regressed a measure of agricultural production or productivity against variables representing agricultural research and extension, often with a view to estimating the rate of return to research.[8] The specification of the determinants of the lag relationship between research investments and production, which involves the

7. For example, Evenson and Kislev (1973) analyzed spillovers related to wheat and maize research, Araji, White and Guenther (1995) looked at spillovers regarding potato research, and Maredia, Ward, and Byerlee (1996) and Traxler and Byerlee (2001) investigated wheat spillovers. Pardey *et al.* (1996) analyzed the U.S. effects of rice and wheat varieties developed by international research centers in the Philippines and Mexico, and Pardey *et al.* (2006) assessed international and institutional crop varietal spillovers into Brazil.

8. A comprehensive reporting and evaluation of this literature is provided by Alston *et al.* (2000a); see also Schuh and Tollini (1978), Norton and Davis (1981), Evenson (2002) and Alston, Andersen, James and Pardey (2010).

dynamics of knowledge creation, depreciation, and utilization, is crucial. Only a few studies have presented much in the way of formal theoretical justification for the particular lag models they have employed in modelling returns to agricultural research.

Table 1 summarizes some key features of research lag distribution models applied in studies of agricultural productivity in OECD countries. This table represents a reworked version of Table 5 in Alston *et al.* (2000a). Until quite recently, it was common to restrict the lag length to be less than 20 years. In the earliest studies, available time series were short and lag lengths were very short, but the more recent studies have tended to use longer lags. Most studies have restricted the lag distribution to be represented by a small number of parameters, both because the time span of the data set is usually not much longer than the assumed maximum lag length, and because the individual lag parameter estimates are unstable and imprecise given the high degree of collinearity between multiple series of lagged research expenditures.[9]

Table 1. Research lag structures in studies of agricultural productivity

Characteristic	Number of estimates	1958-69	1970-79	1980-89	1990-98	1958-98
	Count	*Percentage*				
Research lag length (benefits)						
0 to 10 years	253	9.7	6.2	17.9	12.7	13.4
11 to 20 years	537	41.9	22.0	38.8	22.8	28.5
21 to 30 years	376	0.0	20.7	12.0	25.9	19.9
31 to 40 years	178	0.0	4.3	5.6	14.3	9.4
40 up to ∞ years	141	0.0	9.5	6.6	7.6	7.5
∞ Years	102	35.5	7.5	2.9	5.4	5.4
Unspecified[1]	109	12.9	13.1	3.2	4.9	5.8
Unclear[2]	190	0.0	16.7	12.7	6.3	10.1
Total	1 886	100.0	100.0	100.0	100.0	100.0

This table is based on the full sample of 292 publications reporting 1 886 observations.

1. Unspecified estimates are those for which the research lag length is not made explicit.

2. Lag length is unclear.

Source: Alston *et al.* (2009b), as adapted from Alston *et al.* (2000a).

9. As documented by Alston *et al.* (2000a), 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 2002; 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).

In their application using long-run, state-level data on U.S. agriculture, Alston *et al.* (2010) found in favour of a gamma lag distribution model with a much longer research lag than most previous studies had found — for both theoretical and empirical reasons.[10] Their empirical work supported a research lag of at least 35 years and up to 50 years for U.S. agricultural research, with a peak lag in year 24.[11] This comparatively long lag has implications both for econometric estimates of the effects of research on productivity and the implied rate of return to research.

5. Evidence on the Economic Consequences of Agricultural R&D

This section presents a very brief summary of the evidence in the literature based on the meta-analysis of Alston *et al.* (2000a), which encompasses worldwide evidence on the returns to agricultural R&D, and compares that general evidence with the more recent findings of Alston *et al.* (2010) for the United States. The following section offers some further interpretation of the implications that are briefly presented here. A primary finding from both the review of worldwide evidence and the new results for the United States is that the evidence supports the view that the rate of return to agricultural R&D has been generally very high, implying marginal and average benefit-cost ratios much greater than 1.0. An implication of finding a marginal benefit-cost ratio greater than 1.0 is that it would have been profitable to have invested more; an implication of a marginal benefit-cost ratio much greater than 1.0 is that it would have been very profitable to have invested more. In this sense the evidence indicates consistently that individual nations and the world as a whole have underinvested in agricultural R&D. Unless we have reason to believe that the benefits from agricultural R&D are characterized by sharply diminishing marginal returns, and there is no empirical evidence to support that conjecture, the very large marginal benefit-cost ratios can be interpreted as meaning the underinvestment was substantial.

Overview of Evidence in the Literature

Alston *et al.* (2000a) conducted a comprehensive meta-analysis of studies that had reported estimates of returns to agricultural R&D. Relatively few studies have been published in the ensuing period, so that analysis remains representative of the literature. As the detailed report of the meta-analysis shows, the literature includes studies undertaken in and applying to R&D conducted in many different countries, stratified according to characteristics of the research—such as the field of science, the commodity or other subject matter, and the geopolitical region to which the research applied—as well as a range of details of the method of analysis. A few key points from the meta-analysis are summarized here, leaving the interested reader to go to the report (Alston *et al.*, 2000a) or the summary article (Alston *et al.*, 2000b) for further details.

10. The detailed arguments are laid out in Alston, Norton, and Pardey (1995) and some earlier evidence is presented by Pardey and Craig (1988) and Alston, Craig, and Pardey (1998). See, also Huffman and Evenson (1989). Alston, Craig, and Pardey (1998) discussed the issue of knowledge depreciation drawing on the previous literature and these arguments are restated and refined by Alston, Pardey, and Ruttan (2008), and Alston, Andersen, James and Pardey (2010).

11. Alston, Pardey, and Ruttan (2008) documented the adoption lags for particular agricultural technologies and their results are consistent with relatively long overall lags.

The study sample includes 292 studies that reported a total of 1,852 estimates of rates of return to agricultural R&D, from which Alston *et al.* (2000a) reported an overall mean internal rate of return of 81.3%, with a mode of 40%, and a median of 44.3% (Table 2). After dropping some outliers and incomplete observations, they conducted regression analysis using a sample of 1 128 estimates with a mean of 64.6%, a mode of 28%, and a median of 42.0%. They found results that were generally consistent with expectations but in many cases they could not distinguish statistically significant effects on the estimated rates of return associated with the nature of the research being evaluated, the industry to which it applied, or the evaluation methodology, because the signal-to-noise ratio was too low. Nevertheless, a predominant and persistent finding across the studies was that the rate of return was quite large. The main mass of the distribution of internal rates of return reported in the literature is between 20% and 80% per annum. Other reviews of the literature may not have covered the same studies or in the same ways, but nevertheless reached similar general conclusions—for instance, Evenson (2002), and Fuglie and Heisey (2007).

Table 2. 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

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.

Source: As reported by Alston *et al.* (2009b), based on data reported in Alston *et al.* (2000a).

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

Recent Evidence on U.S. Agricultural R&D

More recently, Alston, Andersen, James, and Pardey (2010) modelled state-specific U.S. agricultural productivity for the period 1949-2002 as a function of public agricultural research and extension investments over 1890-2002. In this study careful attention was paid to the types of methodological issues raised by Alston *et al.* (2000a), in particular to modelling the research lag distribution and the state-to-state spillovers of research impacts. Spillovers between states were represented using a measure of technological closeness based on output mix correlations. The research lag distribution was estimated using a flexible gamma distribution model. The results supported relatively long research lags (an overall lag length of 50 years with a peak impact at 24 years but with most of the impact exhausted within 40 years), with a very substantial share of a state's productivity growth attributable to research conducted by other states and the federal government. These results mean that the national benefits from a state's research investment substantially exceed the own-state benefits, adding to the sources of market failure in agricultural R&D since state governments might be expected to ignore or at least (heavily) discount the spillover benefits to other states.

Table 3 summarizes the results from the authors' preferred model, showing the distribution of own-state and national benefits from state-specific and federal investments in agricultural research and extension in the United States, expressed in terms of benefit-cost ratios and internal rates of return.[12] The results show that marginal increments in investments in agricultural research and extension (R&E) by the 48 contiguous U.S. states generated own-state benefits of between USD 2 and USD 58 per research dollar, averaging USD 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 of between USD 10 and USD 70 per research dollar, averaging USD 32 across the states. The marginal benefit-cost ratio for USDA intramural research was comparable, at USD 18 per dollar invested in research.

The benefit-cost ratios in Table 3 are generally large, and might seem implausibly large to some readers. In fact, however, these ratios are consistent with internal rates of return at the smaller end of the range compared with the general results in the literature as reviewed by Alston *et al.* (2000a) and summarized in Table 2, and as discussed by others

12. There are compelling reasons to report benefit-cost ratios rather than internal rates of return in this instance, as discussed by Alston, Andersen, James and Pardey (2010). Some internal rates of return are reported here to facilitate comparisons with other studies.

(*e.g.* Evenson 2002; Fuglie and Heisey 2007). Specifically the estimates of own-state "private" rates of return ranged from 7.4% to 27.6%, with an average of 18.9% per annum across the states and the estimates of national "social" rates of return ranged from 15.3% to 29.1%, with an average of 22.9% per annum across the states, and the rate of return to USDA intramural research was 18.7% per annum.

These findings confirm the suggestion from Alston and Pardey (2001), that paying greater attention to the temporal and spatial attribution issues is likely to lead to smaller estimates of benefit-cost ratios (or the corresponding internal rates of return to agricultural R&D). Nevertheless even allowing for possible measurement errors and biases, the evidence shows that agricultural research has generated very large dividends. It supports the view that agriculture is characterized by market failures associated with incomplete property rights over inventions and that, in spite of the significant government intervention to correct the market failure, nations have continued to underinvest in agricultural research.

Table 3. 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		*Per cent 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.* (2010).

6. Interpretation of Evidence

Alston *et al.* (2010) showed that their specific estimates of benefit-cost ratios were somewhat sensitive by modelling choices, but the general findings were driven by fundamentals. Specifically, the annual value of agricultural productivity gains is worth many times more than the annual value of expenditures on research. Consequently the benefits from productivity growth attributed to agricultural R&D exceed the costs by an order of magnitude (*i.e.* a factor of 10 or more), regardless of methods of measurement or assumptions about attribution (*e.g.* the shape and length of the R&D lag distribution, inter-regional or inter-institutional spillovers, or the roles of private R&D or extension). This aspect dominates the findings in all of the literature, not just those of Alston *et al.* (2010).

A Simple Approximation

To demonstrate this point, Alston *et al.* (2010) considered the value of the productivity improvements since 1949 compared with the value of the research investments to which those improvements are being compared. Measured U.S. agricultural MFP grew by 1.79% per annum over the period 1949-2002. Compounding the growth rate of 1.79% per year over 53 years, the index of productivity grew from 100 in 1950 to about 258 in 2002—*i.e.* if inputs had been held constant at the 1949 quantities, output would have increased by a factor of 2.6:1. Hence, of the total production, worth USD 174.1 billion in 2002, only 39% or USD 67.3 billion could be accounted for by conventional inputs using 1949 technology, and the remaining USD 106.9 billion is attributable to the factors that gave rise to improved productivity. Among these factors is new technology, developed and adopted as a result of agricultural research and extension.

The figure of USD 106.9 billion refers to benefits in just one year, 2002, associated with productivity improvements since 1949. Alston *et al.* (2010) computed the corresponding measures for each year over the period 1949-2002 by dividing the actual value of agricultural output into (a) a part attributable to actual inputs with 1949 productivity, and (b) a residual attributable to productivity growth since 1949. This stream of residual values was expressed in constant year 2000 dollar terms by dividing the nominal values by the GNP deflator. Compounding forward at a real interest rate of 3% per annum, the stream of residual values is equivalent to a one-time payment of USD 7 335 billion in 2002, an enormous benefit from improved agricultural productivity in the United States during the post-WWII period. The stream of benefits from productivity growth is attributable to various things, such as public and private investments in agricultural research and extension in the United States and elsewhere, improvements in infrastructure, investments in education and improvements in human capital, and spillovers of knowledge and technology from other (non-agricultural) industries.

The present value of expenditures on research and extension over the period 1949-2002 was USD 326 billion. The ratio of the total benefits to these costs is 22.5. However, this crude benefit-cost ratio does not allow for the research lags—which mean that benefits in the early years reflect research expenditures before 1949 and research expenditures in the later years would yield benefits after 2002—, and attributes all of the productivity benefits to public research. Alternative estimates can be obtained by including research expenditures from earlier years, and by allowing that some fraction of

the total benefits is not attributable to public research. For instance, if we allow that half of the benefits were attributable to other sources, the benefit-cost ratio would be cut in half, to 12:1. Or, if we include research expenditures back to 1910 and compare benefits over 1949-2002 with costs over 1910-2002 the benefit-cost ratio falls to 17:1.

Analytical Representation of the Simple Approximation

These crude measures have an advantage in that they avoid the complications of econometric estimation but they entail ad hoc assumptions about the share of benefits attributable to agricultural research and extension, and about the matching of research expenditures against a corresponding period of flows of benefits. Importantly, however, they provide estimates on a similar scale as those that are derived using the more difficult and less transparent econometric approaches, and they illustrate how estimates of benefit-cost ratios are driven by fundamental relationships between rates of productivity growth and their cumulative value, compared with the corresponding figures for annual spending on agricultural R&D.

A relatively simple mathematical model can be used to demonstrate those linkages, and to show how we can extend the general findings to other settings, beyond the U.S. example, such as other OECD countries in which the rates of productivity growth and agricultural research intensities have been similar to their U.S. counterparts. Consider a scenario in which a policy is implemented to spend a fixed real amount, R per year on agricultural R&D in perpetuity. The present value of the costs of this research investment is equal to:

$$(1) \qquad PVC_t = \sum_{n=0}^{\infty} R(1+r)^{-n} = \frac{R}{r}$$

After a lag of L years, this stream of research investments contributes to a compound annual rate of agricultural productivity growth of g in perpetuity. In any future year, the benefits are equal to the difference between the actual value of production, given the productivity growth, and the value in the absence of productivity growth. Assume, for simplicity, that in the absence of this research spending, the real value of agricultural production would be constant at V per year (*i.e.* $V_{t+n} = V$ for all values of n). Then, if $n \geq L$:

$$(2) \qquad B_{t+n} = \left((1+g)^{n-L} - 1\right)V$$

The present value of this stream of benefits is equal to:

$$(3) \qquad PVB_t = \sum_{n=0}^{\infty} B_{t+n}(1+r)^{-n} = \sum_{n=L}^{\infty} \left((1+g)^{n-L} + 1\right)V(1+r)^{-n} = (1+r)^{-L}\frac{V}{r}\left(\frac{g}{r-g}\right).$$

This result holds so long as $r > g$, otherwise it is not defined. That condition is likely to be met in reality given that g is the rate of productivity growth attributable to research investments, typically well less than 2-3% per year while r is the relevant real discount rate, for which 3-5% is a reasonable range.

Defining the benefit-cost ratio, *BCR*, as equal to the present value of benefits divided by the present value of costs,

$$(4) \qquad BCR = \frac{PVB_t}{PVC_t} = \frac{(1+r)^{-L}\frac{V}{r}\left(\frac{g}{r-g}\right)}{\frac{R}{r}} = (1+r)^{-L}\frac{g}{(r-g)}\left(\frac{V}{R}\right)$$

Suppose we use plausible values of $r = 0.05$ (*i.e.* a 5% per annum real interest rate), $L = 10$ years, $g = 0.02$ (*i.e.* a compound productivity growth rate of 2% per year attributable to R&D), and $R/V = 25$ (corresponding to an agricultural research intensity ratio of $i = 0.04$). Using these values, the discount factor is $(1+r)^{-L} = 0.61$, and $BCR = 10.2$.

Table 4 presents the corresponding benefit-cost ratios for a range of values of the parameters in the equation for *BCR*. It can be seen that the benefit-cost ratio is directly proportional to the inverse research intensity ratio (*i.e.* inversely proportional to research spending as a share of the value of output), such that doubling the research intensity halves the benefit-cost ratio. The benefit-cost ratios are similarly sensitive to the other parameters. In particular, if the annual productivity growth rate associated with the given research intensity is reduced from 2% (in the top half of the table) to 1% (in the bottom half of the table), the benefit-cost ratios are reduced by well more than half; if the discount rate is increased from 3% to 5% per annum, again the benefit-cost ratios are reduced by more than half; and if the research lag is doubled from 10 to 20 years, the benefit-cost ratios are reduced by about one-third. Combining these changes, the most favourable combination of parameters results in a benefit-cost ratio that is about 30 times the benefit-cost ratio implied by the least favourable combination, but the least-favourable combination is fairly extreme and even so implies a benefit-cost ratio of well more than one.

Table 4. Approximate benefit-cost ratios implied by a range of parameters

Inverse Research Intensity, *R/V*	Discount Rate, *r* = 3%		Discount Rate, *r* = 5%	
	Research Lag, *L*= 10 years	Research Lag, *L*= 20 years	Research Lag, *L*= 10 years	Research Lag, *L*= 20 years
	***Productivity Growth*, *g* = 2% per year**			
50 (*i* = 2%)	74.4	55.4	20.5	12.6
25 (*i* = 4%)	37.2	27.7	10.2	6.3
	***Productivity Growth*, *g* = 1% per year**			
50 (*i* = 2%)	18.6	13.8	7.7	4.7
25 (*i* = 4%)	9.3	6.9	3.8	2.3

Source: Developed by the author based on formulas in the text.

7. Conclusion

The literature on the economics of agricultural R&D is large. This review has emphasized some key areas where results may be fragile or distorted as a result of modelling choices made by economists. The creation of the "data" used in our analyses is a critical step. Since the interpretation of results often depends crucially on the data, it is incumbent on the data user to invest at least as far as knowing how the data were made, but there is no mechanism for enforcing this investment and it does not appear to have been a focus of effort.

Along with the data, models used for measuring research benefits have improved over the years. Analysis has revealed some areas where findings are sensitive to modelling choices, including the representation of technological change in the model, the treatment of spillovers, and the R&D lag distribution. These are essentially empirical questions that are often difficult to resolve with the available data but must be settled, and can have substantial impacts on the findings. The issue of how to go about specifying the research-induced technical change in models is largely unresolved. Better progress has been made with lags and spillovers. The trend has been to find larger spillover impacts and longer research lags in studies that test for these aspects. Models that inappropriately ignore spillovers or truncate the lag are likely to find higher rates of return to research as a result. Other specification choices, such as how to deal with market distortions from market power of firms, government policy, or environmental externalities, have been shown to have relatively important effects on estimates of the distribution of benefits and relatively little effect on estimates of the total benefits.

As a profession we have amassed a persuasive body of evidence demonstrating that the world as a whole and individual nations have benefited enormously from productivity growth in agriculture, a substantial amount of which has been enabled by technological change resulting from public and private investments in agricultural R&D. The evidence suggests that the benefits have been worth many times more than the costs. This is still so, even if we discount the estimates heavily because we suspect they may have been upwardly biased, perhaps inadvertently through unfortunate choices of methods or limitations in the available data of the types discussed in this review. Since the marginal benefit-cost ratios were much greater than 1.0, it would have been profitable to have invested more, probably much more in agricultural R&D. An implication is that the substantial government intervention notwithstanding, the world has systematically underinvested in agricultural R&D, and is probably continuing to do so.

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