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Science of Science Policy:
Evidence and Lessons from Studies of Agricultural R&D

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1. Introduction

Agricultural science and the related public policies in the United States have been much studied over the nearly 150 years since the U.S. Department of Agriculture was established and the Morrill Land-Grant College Act was passed in 1862. As with science policy generally, issues in agricultural R&D policy have centered on the nature of market failures in agricultural science and innovation, the design of policies and institutions to address those market failures, and measures of the consequences. The professional literature has developed accordingly, with many books and journal articles devoted to issues such as (a) intellectual property and other incentives for private investment; (b) mechanisms for collective action by producer groups; (c) the appropriate division of labor–in funding and conducting agricultural research, education, and technology transfer activities–, between the private sector and various federal, state, and local governments; (d) the organization and management of research resources in the public sector, including the use of competitive grants versus block grants versus congressional earmarks to direct research resources into different jurisdictions and towards different priority areas; (e) the quantification of research investments and activity and the consequences in terms of scientific achievements, productivity patterns, and payoffs. This paper emphasizes this last area of work.

2. Agriculture is Different

Partly for historical reasons, and partly because of the nature of the agricultural sector, relatively detailed high-quality data are available on the sector and policies related to it, and a disproportionate amount of effort of economists has been spent studying agriculture compared with other industrial sectors. Likewise, compared with other industrial sectors, more effort has been spent and more is known about the economics of agricultural science and the related policies (e.g., Macilwain 2010). As discussed by Pardey, Alston and Ruttan (2010), innovation in agriculture differs from innovation elsewhere in the economy in some important ways:

- First, farming is commonly regarded as the archetypal competitive industry comprised of a multitude of atomistic, price-taking firms. This is less true of the elements of the food industry beyond the farm gate, which is relatively concentrated, as is the industrial sector more generally.
- Second, farmers are engaged in inherently biological production processes, using and producing products over which intellectual property protections have been historically weak compared with other industrial sectors.
- Third, agricultural technology has an inherently spatial dimension in that farming uses a lot of land area, and the conditions of production vary with changes in soil, climate, latitude, altitude, and topography. Partly for this reason, individual state governments play a primary role in public agricultural R&D, in a complex partnership with the federal government and in interaction with the private sector.

- Fourth, co-evolving pests and diseases and changing weather and climate give rise to demands for maintenance research, to keep productivity from falling, and for other innovations that reduce the susceptibility of production to these uncontrolled factors.
- Fifth, the beneficiaries are diffuse. A very large share of the world's population is involved directly in agricultural production, though only a very small share in high-income countries, like the United States. Consumers are the primary beneficiaries from agricultural innovation, and everyone is a consumer of agricultural products. The United States plays significant roles in generating agricultural technologies for other countries, helping in this way to feed the world.

These special characteristics of agriculture influence the nature and extent of market failure in agricultural innovation such that the appropriate roles of government in industrial R&D differ correspondingly in detail between agriculture and other industrial sectors of the economy. Even so, there are significant elements of common ground, and the study of the economics of agricultural science and related policy yields insights into the economics of science and lessons for science policy more generally–especially in relation to attribution issues.

3. Key Points

This paper summarize the main findings from the literature on the modeling and measuring the benefits from agricultural R&D and distills some lessons for economic analysis and policy both in the agricultural sector and beyond, drawing mainly on the book by Alston, Andersen, James and Pardey (AAJP, 2010).[1] Key points are:

- Accurate attribution, matching streams of research benefits appropriately to streams of investments, is critical. Many studies have overstated rates of return to research because they did not allow sufficiently long R&D lags or did not allow appropriately for knowledge and technology spillovers. After correcting for attribution errors and other biases, the measured rates of return are significantly reduced, but nevertheless very high.
- U.S. public agricultural R&D has earned very high returns, with benefit-cost ratios in the range of 20:1 and higher. This means that, in spite of significant government intervention to encourage private investment, and finance and conduct research in public institutions, the United States has persistently underinvested in agricultural R&D.
- Recent trends indicate declining support for agricultural R&D and a diversion of research resources away from high-payoff farm productivity enhancement in conjunction with a slowdown in agricultural productivity growth. Institutional innovation may be necessary to enhance the total investment in agricultural R&D, capitalize on the high research payoffs, and restore productivity growth to reduce pressure on food prices and natural resource stocks.

[1] AAJP (2010) present detailed documentation and extensive and definitive new evidence on (a) U.S. state-level and national agricultural inputs, outputs, and productivity patterns over the 20th century, especially since WWII, (b) U.S. state-level and national agricultural R&D policy, with detailed data on investments in agricultural R&D since 1890, (c) the econometric relationships between investments in agricultural R&D and productivity, (d) the implied benefit-cost ratios, and (e) a detailed assessment and interpretation of the evidence. They also present a detailed review of previous studies of agricultural research returns, their methods, and findings.

4. Models of R&D and Productivity and Returns to Research

Methods of benefit-cost analysis have been applied extensively to public agricultural research, development, and extension (R,D&E). Over the past half century or so, hundreds of studies have been published reporting measures of agricultural productivity, the effects of agricultural R,D&E on agricultural innovation and productivity patterns, and the resulting social payoffs to investments in agricultural R,D&E. Beginning with Schultz (1953), agricultural economists have used supply and demand models of commodity markets to represent agricultural research impacts. In the standard model of research benefits (e.g., see Alston, Norton, and Pardey 1995), research causes a 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 and producer surplus.

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. 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. Some issues in the literature relate to the methods used for measuring 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. 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.

Measures of the size and distribution of research benefits can be affected by various complications that can be introduced to extend the basic model. The basic model assumes the results from research are provided to the industry for free by the government. Models that allow for proprietary technology have not been used much in the applied work to date on returns to agricultural research, 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 those resulting from policy distortions, the exercise of market power by middlemen, or environmental externalities. 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. Most of the studies reporting rates of return to agricultural R,D&E 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.

5. Attribution Problems in Models of Research Impacts

Attribution problems have bedeviled 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&E (the spatial and institutional-cum-sectoral attribution problem), and (b) in identifying the research lag structure (the temporal attribution problem).

Spillovers. 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. The relevant agroecological region in which agricultural research results are applicable may extend well beyond the borders of its geopolitical source, and the extent of spillovers will depend on the degree of agrocecological similarity. This aspect of knowledge and technology spillovers that is significant for agricultural R&D may also be relevant for some other areas of public research (e.g., human health) but is less relevant for general industrial R&D where, as discussed by AAJP (2010), the literature on spillovers emphasizes inter-industry and inter-firm aspects with much less emphasis on space per se.

R&D Lags. 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. The specification of the determinants of the lag relationship between research investments and production, which involves the 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 modeling returns to agricultural research. 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. In their application using long-run, state-level data on U.S. agriculture, AAJP (2010) found theoretical and empirical support for a gamma lag distribution model with a much longer research lag than most previous studies had found. 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. 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.

Studies of non-agricultural industrial R&D often use a very short geometric lag distribution model. This lag shape is implausible, because it does not allow for the time taken to generate the research results and develop useful innovations. In typical applications, assumptions are made about the rate of knowledge depreciation that together with the geometric form imply a very short effective lag period over which research investments yield benefits. Studies of agricultural R&D that have tested these assumptions have rejected them in favor of models that imply a different lag shape and a much longer overall lag, and significantly different implications for the measured returns to research.

6. Evidence on the Economic Consequences of Agricultural R,D&E

Alston et al. (2000) conducted a comprehensive meta-analysis of studies that had reported estimates of returns to agricultural R,D&E. The literature includes studies undertaken in and applying to R,D&E 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. It includes evaluations applied to individual research projects or research institutions, as well as others applied to aggregate state or national programs of research.

The study sample includes 292 studies that reported a total of 1,852 estimates of rates of return to agricultural R,D&E, from which Alston et al. (2000) reported an overall mean internal rate of return of 81.3 percent per annum, with a mode of 40 percent, and a median of 44.3 percent. After dropping some outliers and incomplete observations, they conducted regression analysis using a sample of 1,128 estimates with a mean of 64.6 percent, a mode of 28 percent, and a median of 42.0 percent. 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 percent per annum.

Alston et al. (2000) concluded that the evidence suggests that agricultural R,D&E 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.

More recently, AAJP (2010) modeled panel data of state-specific U.S. agricultural productivity for the period 1949–2002 as a function of public agricultural research and extension investments over the years 1890–2002. In this study careful attention was paid to the types of methodological issues raised by Alston et al. (2000), in particular to modeling 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&E since state governments might be expected to ignore or at least (heavily) discount the spillover benefits to other states.

Table 1 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.[2] 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 $2 and $58 per research dollar, averaging $21 across the states (the lower benefit-cost ratios were generally for the states with smaller and shrinking agricultural sectors, especially in New England). Allowing for the spillover benefits into other states, state-specific agricultural research investments generated national benefits of between $10 and $70 per research dollar, averaging $32 across the states. The marginal benefit-cost ratio for USDA intramural research was comparable, at $18 per dollar invested in research.

[Table 1: *Benefit-cost ratios and internal rates of return for U.S. agricultural R,D&E*]

[2] There are compelling reasons to report benefit-cost ratios rather than internal rates of return in this instance, as discussed by AAJP (2010). Some internal rates of return are reported here to facilitate comparisons.

The benefit-cost ratios in Table 1 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. (2000) and as discussed by others (e.g., Evenson 2002; Fuglie and Heisey 2007). Specifically the AAJP estimates of own-state rates of return range from 7.4 to 27.6 percent, with an average of 18.9 percent per annum across the states. The corresponding estimates of national rates of return, including spillover benefits to other states, range from 15.3 to 29.1 percent, with an average of 22.9 percent per annum across the states; and the estimated rate of return to USDA intramural research is 18.7 percent 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&E). 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, states and nations have continued to underinvest in agricultural research both from a narrow own-state and a broader national perspective.

AAJP (2010) showed that their specific estimates of benefit-cost ratios were somewhat sensitive to modeling 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&E 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&E lag distribution, inter-regional or inter-institutional spillovers, or the roles of private R,D&E or extension). This aspect dominates the findings in all of the literature on returns to agricultural R,D&E, not just those of AAJP (2010).

7. Lessons Regarding Methods and Measures

AAJP (2010) paid particular attention to the modeling of R&D lags, for which the extensive data base is advantageous, to spatial spillovers among different R&D jurisdictions (in this case States), and to the potential influence of modeling assumptions and methods of measurement on findings. Their findings in this context are relevant to industrial R&D generally, especially those concerning the R&D lag relationship. As noted above, the specification of the lag relationship can affect findings, and studies often impose implausible restrictions on the shape and length of the research lag distribution that are likely to lead to upwards biases in estimated payoffs. Similar biases can be caused by the misspecification of the spillover relationship, which is another important element of the attribution problem.

This discussion has set aside some other issues related to methods and measures, many of which are explored in AAJP (2010) or Alston, Norton and Pardey (1998). Serious effort is required to obtain meaningful measures of outputs of goods and services and the inputs used to produce them, and of investments in R,D&E and the outputs from that investment. Findings are to some extent contingent on the quality of the data that goes into any analysis, and the evaluation of returns to research entails extensive data transformation prior to as well as in the analysis. It is therefore important for those who create and use such data to be conscious of the potential fragility of results that are contingent on data-creation procedures and other modeling choices, and where possible to gauge the robustness of the results relative to choices made by the analyst and other sources of uncertainty.

In the case of U.S. agricultural R,D&E, the value of annual agricultural productivity growth is worth many times more than annual expenditure on R,D&E. Hence, even if only a fraction of that productivity growth is attributable to R,D&E, and even if the lags are very long before the benefits are realized, the benefit-cost ratio will be favorable. AAJP (2010) demonstrated this point quantitatively for U.S. agricultural R,D&E. A strong qualitative conclusion follows: that agricultural R,D&E has been a very profitable investment. More specific, quantitative statements about the benefit-cost ratio depend on the details of attribution, by econometric means or otherwise, that is subject to measurement error. This intuitive common-sense approach may well be applicable to other sectors of the economy.

8. Policy Issues and Analysis

In the United States, about half of the total agricultural RD&E is conducted and funded by the private sector while the other half is conducted mainly by state agricultural experiment stations using a mix of federal and state funds. Many issues arise concerning the appropriate balance among sources of funds and division of labor among the various private and public sector agencies; appropriate mechanisms for managing and allocating the research resources; and the appropriate roles for the federal government in conducting its own research providing support as well as institutional arrangements and incentives for others. Much measurement work and analysis has been undertaken by agricultural economists and others to inform policy related to these issues.

The available benefit-cost evidence indicates that the government intervention has been effective, in the sense that policies in place and the investments they have engendered have yielded very handsome dividends. The evidence supports the use of federal funds as incentives to encourage states to invest in research that has significant spillover benefits to other states. At the same time the evidence demonstrates a very substantial government failure in that, in spite of the extensive government intervention, the nation as a whole and individual state governments have persistently underinvested. Moreover, some other recent work (e.g., see Alston, Babcock and Pardey 2010) suggests a significant slowdown in the rate of agricultural productivity growth in the United States both in absolute terms and relative to countries that have been increasing their investments in agricultural R&D (e.g., China, India, and Brazil), a further potential reason for reinvigorating U.S. investments in agricultural research. Yet, while the U.S. government spends over $100 billion per year in the Farm Bill, the Research Title attracts less than 2 percent of that total, only one-tenth of the amount spent on farm commodity subsidies in typical years.

Even so, if anything, Federal and State government support for agricultural science is shrinking (e.g., see Pardey and Alston 2010).

Extensive evidence of high rates of return alone has not been sufficient to sustain government support for agricultural research in the United States and most other developed countries. Much agricultural science is more of a commodity- or industry-specific collective good rather than a national or state-specific public good. An alternative to public funding using general government revenues is to finance certain types of industrial research in agriculture and possibly other industries using output taxes—a type of hypothecated tax—as used to fund agricultural research extensively in Australia, through Rural Research & Development Corporations (RDCs). Such an approach may well be relevant to address the persistent and possibly worsening U.S. underinvestment in agricultural R,D&E, but to be effective it is likely to require some degree of matching support from the government (e.g., see Alston, Freebairn, and James 2004). Issues about appropriate management and direction of the resources, the balance of sources of funding and the appropriate focus of the investments are inevitable (e.g., see Productivity Commission 2010).

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Table 1: *Benefit-cost ratios and internal rates of return for U.S. agricultural R,D&E*

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, Andersen, James, and Pardey (2010).