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The Economics of Agricultural R&D

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Abstract

Agricultural research has transformed agriculture and in doing so contributed to the transformation of economies. Economic issues arise because agricultural research is subject to various market failures, because the resulting innovations and technological changes have important economic consequences for net income and its distribution, and because the consequences are difficult to discern and attribute. Economists have developed models and measures of the economic consequences of agricultural R&D and related policies in contributions that relate to a very broad literature ranging across production economics, development economics, industrial organization, economic history, welfare economics, political economy, econometrics, and so on. A key general 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 modeling 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.

1. INTRODUCTION

Agricultural research has transformed agriculture and in doing so has contributed to the transformation of whole economies. Economic and policy issues arise because agricultural research is subject to various market failures, because the resulting innovations and technological changes have important economic consequences for net income and its distribution among individuals and among factors of production, and because the consequences are difficult to discern. These issues have been studied by economists and documented in a literature on the economics of agricultural research and development (R&D) that began as such in the 1950s, with work by T.W. Schultz and others.

Over the ensuing half century or so, economists have developed models and measures of the economic consequences of agricultural R&D and related policies in contributions that relate to a very broad literature, drawing on and at times contributing to the full range of subfields of economics.[1] For instance, some contributions extend back to the foundations of production economics, the measures of inputs and outputs, and their relationships to one another, as we attempt to obtain better measures of productivity. Others relate to the modern literature on industrial organization as we attempt to understand the role of market power of firms with intellectual property rights to inventions. Yet others relate to income distribution in multimarket settings, whether in the context of rich-country agriculture and concerns for displaced labor or in developing countries where a general equilibrium approach is necessitated by the role of agriculture in the economy as a whole. At some level, then, to understand the economic literature on agricultural R&D requires an appreciation of its relationship to the major subfields of economics (such as econometrics, labor economics, public economics, production economics, economic history, industrial organization, or operations research) to which it contributes and from which it draws ideas, methodological approaches, and tools and techniques. Within the constraints of this review, however, for the most part we treat the literature on the economics of agricultural R&D in isolation, only occasionally drawing attention to the linkages to the broader literature.

In this review, we focus on the role of methods used by economists and their implications for findings about research impacts. We cover the mainstream issues and the bulk of the published work on the economics of agricultural R&D, dealing with conceptual models of the impacts of agricultural research, data and methods for measuring the impacts, the resulting measures of the impacts, and the meaning of those measures.

Section 2 is organized around supply and demand models of the size and distribution of research impacts among producers, consumers, and others in the marketing chain. Much of the literature in this area has concerned the role of modeling assumptions in determining the findings—in particular, assumptions about the nature of research-induced technological changes and how they are represented in the model, as well as assumptions about the form of competition, and related issues. We present the main ideas from that literature and attempt a synthesis.

An important and often underappreciated type of economic research is contributed by studies that describe research institutions and quantify research investments or by

[1]Griliches (2001) 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 & 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" (p. 23).

studies that develop measures of agricultural outputs, inputs, and productivity, and thereby provide data for econometric and other modeling studies. Section 3 documents some key contributions of this type and touches on some enduring issues related to the data.

Section 4 discusses a different set of methodological questions that arise in modeling agricultural innovation. In particular, the treatment of (spatial) spillovers and research lag structures can be seen both as elements of the general attribution problem raised by Alston & Pardey (2001) and as sources of specification bias with implications for the interpretation of findings. A related literature linking innovation processes to technology development and economic impacts deals with the rate, extent, and nature of technology adoption and diffusion processes.

Section 5 reports key findings about the impacts of agricultural research in terms of its consequences for the rate of technological change (or productivity growth) and its factor bias as well as the rate of return to the investments. The rate of return evidence generally indicates 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. Section 6 summarizes and concludes the review.

2. MODELS OF THE SIZE AND DISTRIBUTION OF RESEARCH BENEFITS

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 & Tisdell (1971), Duncan (1972), Akino & Hayami (1975), and Scobie (1976), among others.[2,3] In a standard model of research benefits, 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 as well as 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 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. Hence, Griliches (1958) proposed the approximation $GARB = kPQ$, where P is the commodity price and Q is the annual quantity to which the supply shift applies.[4] 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, those based on adoption rates combined

[2]Although this seems to be a natural approach for technologies embodied in particular inputs, like seeds, it is less well-suited to many other kinds of agricultural R&D. An alternative approach may be to use a model of supply and demand for agricultural science.

[3]Some studies leave this model implicit when inferring a rate of return to research from the parameters of an econometric model of production (e.g., Evenson 1967) or when using short-cut approximations to measure benefits (e.g., Griliches 1958).

[4]As noted by Alston et al. (1995, pp. 60–61), and more recently elaborated by Oehmke & 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.

with changes in experimental yields or commercial yields or others based on changes in total factor productivity. Other important issues are the size and structure of the market to which the shift factor pertains as well as the time-varying magnitude of the shift.

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 (see Alston et al. 1995). The nature of the research-induced supply shift has been controversial because it matters for results and is not easy to observe. Lindner & Jarrett (1978, 1980), Rose (1980), and Wise & Fell (1980) discussed the underlying conditions for and likelihood of parallel, pivotal, convergent, and divergent supply shifts driven by research. They also considered the implications of the alternatives for the size and distribution of total research benefits (see also Voon & Edwards 1991, Oehmke & Crawford 2002, among others). One point demonstrated by this literature was that the assumption of a linear supply function that is inelastic in the neighborhood of the equilibrium implies a positive intercept on the quantity axis, which is both implausible and a source of awkwardness when measuring the benefits from research-induced supply shifts that require extrapolating supply back to the origin. A similar problem arises with constant elasticity supply models (the main alternative to the linear model in this literature), which also become implausible at low prices and quantities.

One solution to this set of problems is to assume an alternative functional form for the supply function, as illustrated in **Figure 1**, where D_0 represents the demand for U.S. agricultural output and S_0 represents the supply.[5] Suppose a research-induced technical change causes supply to shift down in parallel to S_1 and, as a result, quantity produced and consumed increases from Q_0 to Q_1 and price falls from P_0 to P_1. Accepting Harberger's (1971) postulates so that changes in economic surplus are the relevant welfare measures, the total benefits from the research-induced supply shift are equal to the area between the two supply curves, behind the demand curve, and this is equal to area (B + C + E + F + G). Of that total, the consumer benefit is equal to area (A + B + F) and the producer benefit is equal to area (C + G) given the assumption of a vertically parallel supply shift, which means area A is equal to area E. These shares of the total benefits are distributed according to the elasticities of supply (ε) and demand (η, representing the absolute value), where the producer share is approximately $\eta/(\eta + \varepsilon)$ and the consumer share is approximately $\varepsilon/(\eta + \varepsilon)$. Alternatively, suppose research causes a pivotal supply shift (i.e., holding the price intercept constant at b) that would have the same price and quantity effects. The total research benefits are now only roughly one-half of those from a parallel shift, but the consumer benefits are the same as from the corresponding parallel shift such that the producer benefits must be smaller, possibly negative.

To illustrate the role of elasticities in conjunction with the nature of the supply shift in determining the size and distribution of research benefits we use an algebraic representation of the model depicted in **Figure 1**, as follows:

$$P = (1 - k_1)b + (1 - k_2)BQ^{\beta} \text{ (supply)}; \tag{1}$$

[5]This supply function nests linear and constant elasticity models as special cases and has the virtue of a positive price intercept (or shutdown price) while permitting supply to be inelastic in the vicinity of the equilibrium (see Lynam & Jones 1984, Pachico et al. 1987, Alston & Wohlgenant 1989).

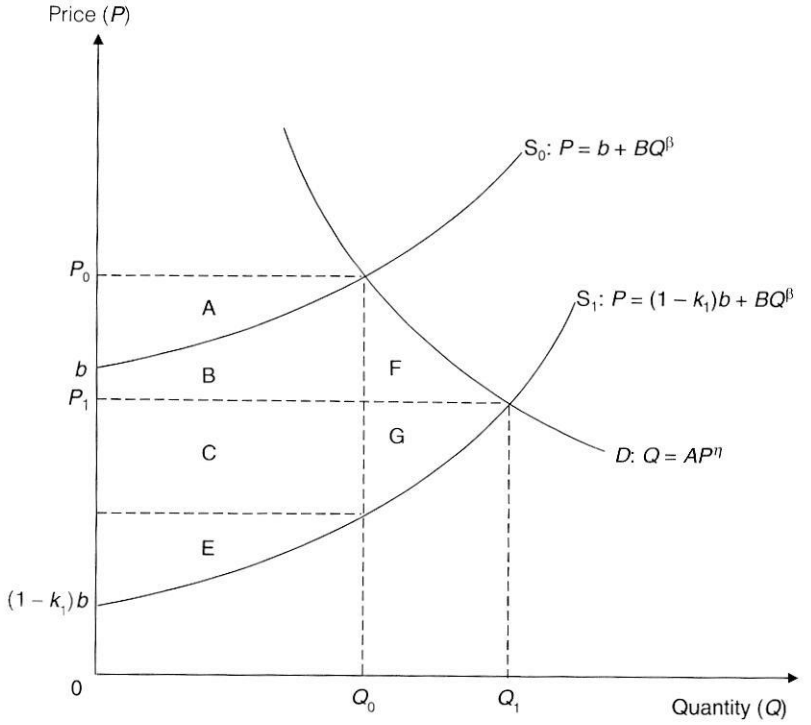

Figure 1

Price, quantity, and welfare effects of agricultural R&D.

$$Q = AP^{\eta} \text{ (demand)}. \tag{2}$$

This model nests as special cases both the linear supply model ($\beta = 1$) and the constant elasticity supply model ($b = 0$) and can combine these functional form alternatives with alternative types of supply shifts by using alternative combinations of values for k_1 (which implies parallel shifts in the price direction) and k_2 (which implies multiplicative shifts in the quantity direction); B and A are "slope" parameters. Although it cannot be solved analytically in its general form for the equilibrium price and quantity, this model can be solved numerically given particular values of parameters. **Table 1** shows the resulting estimates of producer benefits as a share of total benefits for three different kinds of 1% shifts down of the supply function: (*a*) vertically "parallel" ($k_1 = 0.01$, $k_2 = 0$); (*b*) "pivotal" (or multiplicative in the quantity direction, $k_1 = 0$, $k_2 = 0.01$); and (*c*) "proportional" (or multiplicative in the price direction, $k_1 = k_2 = 0.01$)—essentially combining a parallel shift and a pivotal shift. This range of parameters, which implies values for the elasticity of supply at the initial equilibrium ranging from 0.33 to 2.0, is combined with demand elasticities from 0.5 to ∞.[6]

[6]Small elasticities of demand are appropriate for most agricultural commodities in the context of a closed economy model. But larger elasticities are appropriate for traded (or tradable) goods, and in many cases, either countries are small countries in trade (facing excess demand elasticities for domestic output approaching infinity) or they would be but for trade barriers. More elaborate models are required to partition the "consumer surplus" in **Figure 1** among nations and to deal with the consequences of trade-distorting policies in such cases.

Table 1 Producer shares (percentage) of research benefits and their determinants[a]

Supply function parameters			Demand elasticity (absolute value)				
β	b	Elasticity (ε)	0.5	1.0	1.5	2.0	4.0
Parameter values			Producer shares of benefits (percent)				
Pivotal supply shift: $k_1 = 0.00$, $k_2 = 0.01$							
4.00	0.25	0.33	−100	−25	9	29	62
4.00	0.50	0.50	−150	−67	−25	0	44
4.00	0.75	1.00	−234	−150	−100	−67	0
2.00	0.25	0.67	−71	−20	8	25	57
2.00	0.50	1.00	−100	−50	−20	0	40
2.00	0.75	2.00	−140	−100	−72	−50	0
Proportional supply shift: $k_1 = 0.01$, $k_2 = 0.01$							
4.00	0.25	0.33	0	37	55	64	81
4.00	0.50	0.50	17	44	58	67	82
4.00	0.75	1.00	17	38	50	59	75
2.00	0.25	0.67	−14	20	38	50	71
2.00	0.50	1.00	0	25	40	50	70
2.00	0.75	2.00	4	20	32	40	60
Parallel supply shift: $k_1 = 0.01$, $k_2 = 0.00$							
4.00	0.25	0.33	60	75	82	86	92
4.00	0.50	0.50	50	67	75	80	89
4.00	0.75	1.00	34	50	60	67	80
2.00	0.25	0.67	43	60	69	75	86
2.00	0.50	1.00	33	50	60	67	80
2.00	0.75	2.00	20	34	43	50	67

[a]Entries in this table are measures of producer benefits as a percentage of the total benefits from the supply shift. The parameter b represents the shutdown price as a fraction of the initial price, and the parameter β is the exponent of the quantity in the price-dependent supply response function, such that a larger value of β tends to imply a smaller supply elasticity, as does a smaller value of b.

With a linear model, producers lose from a pivotal shift either if demand is inelastic or if demand is elastic but less elastic than supply. Somewhat similar results are found here for the nonlinear model. Producers do not benefit from a pivotal shift unless demand is elastic, and much more elastic than supply. In contrast, with a parallel research-induced

supply shift, producers gain a substantial share of the benefits, especially if supply is relatively inelastic. And, with the proportional shift, although the producer share of benefits is smaller than for the parallel shift, it is still in the range of 30–60% of total benefits given the more likely values for the supply and demand elasticities.

The possibility of losses to producers in aggregate is often discounted, on the grounds either that demand is relatively elastic or that a parallel research-induced supply shift is relatively likely (or that the pivotal shift seems comparatively unlikely), but concrete empirical evidence on that issue has been elusive to date. Thus, even when we can be assured of benefits to the nation, some uncertainty remains about the distribution of benefits between producers and consumers.[7]

2.1. Distribution of Benefits Among Producers

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), so individual producers or groups of producers may be uncertain about their benefits from a given research investment because of uncertainty over what technology may be developed and who will adopt it and when. Timing issues are also important. The lags between investing in agricultural research and reaping benefits are very long—recent results from Alston et al. (2009), reinforced with evidence presented by Alston et al. (2008), suggest lags as long as 10–15 years before important benefits begin to be realized, with streams of benefits extending for 40 years and more after the initial investment. This means that the distributional question has an intergenerational dimension to add to the other dimensions related to factor ownership and adoption patterns.

In addition to issues about the distribution of benefits and costs between adopters and nonadopters, there may be further distributional issues associated with how the "producer surplus" is distributed among factor suppliers: Do land owners benefit at the expense of suppliers of farm labor, including farm operators, or vice versa? To illustrate the key ideas, we can divide the total surplus into benefits accruing to "farmers" (i.e., the suppliers of land and managerial inputs used in agricultural production) and "others" (i.e., the suppliers of other inputs, including off-farm labor, purchased by farmers and other agribusiness inputs used in activities beyond the farm gate). Following Alston et al. (1995, pp. 246–50), we can measure these outcomes using a variant of the Muth (1964) two-factor, single-commodity market in which research gives rise to factor-augmenting changes in technology, which imply shifts in factor demand and product supply. Here, producer benefits correspond to producer surplus measured off the supply function for the factor supplied by farmers, and under the maintained assumption of competition, national benefits are given by the sum of changes in producer surplus across factor suppliers plus consumer surplus in the output market.

[7]All of this discussion abstracts from the dynamics of supply response to price, which means that the elasticity of supply (and, in some cases, the elasticity of demand) becomes greater with increases in the length of run. The dynamics of supply response to price—either alone or in combination with the spatial dynamics of the research-innovation-adoption process—mean that the pattern of research benefits evolves over time in complex ways that vary from case to case. A consideration of these dynamic aspects adds to the ambiguity of results derived from relatively simple comparative static analysis.

In this setting, it is not necessary to extrapolate any of the functions back to the origin to measure the changes in welfare associated with technical changes specified in this way. Local approximations to the functions are adequate for measuring the impacts of the small displacements involved. By measuring producer welfare impacts in the factor markets, we avoid the problem of having to specify the nature of the research-induced shift in the commodity supply function. Even so, we cannot avoid the fact that the measure of research benefits will depend on the assumed nature of the research-induced technical changes, which, with other assumptions, will implicitly define the nature of the shift of the commodity supply function. A difference is that we may have a reasonable intuitive basis for assuming a particular type of technological change (e.g., factor augmenting, neutral, or biased) in situations where we do not have such a basis for assuming a particular form of research-induced product supply shift.

In fact, however, the very specification of technology defined at the industry level or the use of a representative firm model will condition distributional findings: The approach generally entails technological changes that are consistent with multiplicative shifts of supply functions and the associated implications for distribution of benefits. For instance, if simple models such as the Cobb-Douglas model or the Constant Elasticity of Substitution model are used to represent the production function, factor-augmenting technological change (whether neutral across all factors or biased to augment just one factor) or the inclusion of research as a separate input will imply proportional (pivotal or otherwise divergent) supply curve shifts. More flexible functional forms for the production function may imply different types of technological possibilities, but such functions may prove difficult to work with. The same issues arise if, rather than a production function, we begin by specifying a cost or profit function, and we derive the implied output supply functions. Martin & Alston (1997) exemplify this approach to discussing the effects of R&D on market outcomes. Here, as they showed, parallel shifts can be derived but only if technological change enters the profit or cost function as a separate input. If the R&D is factor augmenting, or has the effect of reducing the cost for "effective" inputs, however, a multiplicative supply shift is implied.

If an industry is made up of diverse individual firms, it may not be well represented by an approach that implicitly or explicitly assumes an industry technology or a representative firm. Wohlgenant (1997) illustrated the roles of entry and exit of firms, variety in cost conditions among firms, and differential rates of adoption in determining the nature of the shift of the industry supply function (see also Foster & Rausser 1993). Consider an industry made up of heterogeneous firms in which firm entry and exit are key components of adjustment along the industry supply curve in response to price changes. A rising industry supply curve may reflect progressive increments in firms' reservation prices for entry, indicating variations in their opportunity costs of the quasi-fixed factors earning quasi-rents that make up producer surplus. A factor-augmenting technical change could give rise to proportional shifts in individual firm supply functions (in the context of the types of production, cost, or profit functions discussed above), while leaving their reservation prices unaffected, and the resulting shift in the industry supply function may be approximately proportional or pivotal as well. In contrast, similar per-unit reductions in reservation prices across firms would imply an approximately parallel industry supply curve shift, such that marginal and average costs would fall by the same amount per unit. More generally, technical changes may involve combinations of effects on the slopes and intercepts of individual firm supply functions

as well as differential effects on different types of firms. Thus, research-induced technological change may plausibly give rise to supply curve shifts that are divergent, convergent, or parallel—depending on the nature of the industry, its technology, and the technological change—in ways that make the issue difficult to judge either *ex ante* or *ex post*. Because specification choices are unavoidable, it makes sense to be aware of the implications of the main alternative specifications for findings about the distribution of research benefits.

2.2. Extensions to the Basic Model

Measures of the size and distribution of research benefits will be affected by various complications that can be introduced to extend the basic model represented in **Figure 1**. 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.[8] It becomes slightly more complicated when we allow for technological spillovers in the same model. More elaborate and complex multimarket models are implied if we want to disaggregate the market structure either (*a*) vertically in order to represent different stages of the marketing chain or (*b*) horizontally in order to represent different geopolitical or spatial markets for a given product or different products (including different qualities of the same product). Alston et al. (1995) laid out the basic theory for these approaches, and a number of studies have reported specific applications (among the many examples are Mullen et al. 1989, Freebairn 1992, Frisvold 1997, Wohlgenant 1997, Davis & Espinoza 1998, and Zhao et al. 2000).

A further dimension for extension to the basic model is to allow for the case of proprietary technology. The basic model treats the technological change as essentially exogenous, a reasonable treatment for the case of public research from which the results are freely accessible, which is the stereotypical application. However, this model is not appropriate for proprietary technology resulting from private research over which the inventor has (often monopoly) property rights, such as the fruits of modern biotechnology. In an important contribution, Moschini & Lapan (1997) extended the basic model to deal with proprietary research that could lead to a drastic innovation or a nondrastic innovation that would be priced in either case so as to entirely eliminate the pre-existing technology. A number of subsequent studies have extended the ideas, but these types of conceptual developments have not been incorporated 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, on the one hand, and others including farmers, consumers, and agribusiness.[9]

[8]A significant complication in evaluating the supply-shifting consequences of agricultural research is that, because of the biological basis of agricultural production, many agricultural technologies have distinctive location-specific attributes. The specific location of firms may well affect their decisions about adoption of technology and the resulting factor demand and output supply responses to R&D, with implications for the aggregate industry-wide responses, even within a given spatial or market aggregate. Substantive efforts are under way to calibrate measured supply shifts in ways that take explicit account of these spatial heterogeneities (for example, see **http://www.HarvestChoice.org**).

[9]Moschini & Lapan (1997) treated the research effort and the research result as exogenous, whereas Alston & Venner (2002) developed a model in which the research effort was chosen by the biotech firm. See also Frisvold et al. (1999), Falck-Zepeda et al. (2000), Qaim (2003), and Lapan & Moschini (2004).

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, for example, (*a*) those resulting from the introduction of distortions associated with government policies such as farm commodity programs or trade barriers, including the failure to impose optimal trade taxes in the large-country case; (*b*) those resulting from the exercise of market power by middlemen (e.g., Huang & Sexton 1998); and (*c*) those resulting from environmental externalities (e.g., Antle & Pingali 1994). In this context, the main effect of a market distortion is to change the distribution of research benefits, with comparatively small effects on the total benefits. These changes in the distribution of benefits (and the total benefits) depend on the nature of the market distortion, along with the other market characteristics and the nature of the research-induced technological change, which together determine the potential research benefits in an undistorted setting.

Alston et al. (1988) identified and Alston & Martin (1995) subsequently proved a key aspect of the relationship between the distorted and undistorted research benefits. Specifically, research benefits in the presence of a distortion (ΔW^{ACT}) are equal to benefits in the absence of the distortion (ΔW^{MAX}) minus the effects of research on the deadweight losses from the distortion (ΔDWL, where we define $DWL = W^{ACT} - W^{MAX}$)—i.e., $\Delta W^{ACT} = \Delta W^{MAX} - \Delta DWL$. Thus, research benefits may be smaller or greater than in the absence of the distortion, depending on whether the research-induced technological change exacerbates or mitigates, respectively, the deadweight loss from the distortion—a result that depends, in turn, on the specific nature of a distortion and the other features of the market in which it applies. This simple but powerful result encompasses many ideas and is broadly applicable to any second-best analysis, not just this specific category. It helps to account for a variety of specific results in the literature on research benefits in a distorted market setting (e.g., Murphy et al. 1993, Chambers & Lopez 1993). For instance, immiserizing technological change requires that the effect of research be to worsen the consequences of an existing distortion sufficiently to more than outweigh the maximum potential benefits, which is a rather extreme outcome.

2.3. Political Economy Models

Models of agricultural research in a distorted market setting have been used to draw inferences about implications of market distortions for the rate of investment in agricultural research and thus the rate and direction of technological change (e.g., Hayami & Ruttan 1971, Schultz 1978, Mellor & Johnston 1984). Further wrinkles are added if we treat the distortions as endogenous, being determined jointly with the research investment and thus the technological change in a political economy or interest group model: Studies in this vein include, among others, Rausser (1982), Gardner (1988), de Gorter & Zilberman (1990), Rausser & Foster (1990), de Gorter et al. (1992), Alston & Pardey (1993), Foster & Rausser (1993), and de Gorter & Swinnen (1998, 2002). For instance, de Gorter & Zilberman (1990) used a model of industry technology with inelastic demand in which, consistent with the discussion in Section 2.1, farmers would lose from research in an undistorted setting but would benefit from research in the presence of a target price policy. Thus, they suggest we can account for and justify farm support policies as having been introduced to make possible socially beneficial research that otherwise would not have been politically acceptable to agricultural interests.

Political economy models that suppose agricultural research and farm program policies are chosen jointly to maximize a single criterion function typically involve two important abstractions from reality. First, the models assume a single government choosing combinations of policies to maximize a single criterion function. However, in countries such as the United States, the policies are chosen by different governments. Farm program policies are determined federally, whereas public agricultural research investments are predominantly the province of state government agencies, albeit using funds from a mixture of sources including state governments and various arms of the federal government.[10,11] Second, the models treat the consequences of today's R&D policies as though they are felt immediately along with the effects of today's farm commodity policies, but the impacts of today's research are realized only after long lags, measured in decades. The research policies that are interacting with and determining the impacts of today's commodity programs were implemented by the governments in power 20 years ago—the agricultural R&D policies established under George H.W. Bush, not George W. Bush, will determine the impact of farm program policies to be introduced by President Obama.[12]

The extent to which the results from the models are conditioned by these abstractions remains a matter for conjecture. To be sure, research policies chosen by any of the 50 state governments will be influenced by the present and prospective price policies to be implemented by the federal government, and the price policies introduced by the federal government in its periodic farm bills will have been influenced by the federal and state agricultural R&D programs over the previous decades. However, the relationships are many dimensional and multiperiod, with recursive rather than simultaneous causation, and thus are unlikely to be represented accurately by a simple static trade-off of welfare among producers, consumers, and taxpayers to maximize a single objective function.

3. RESEARCH THAT CREATES DATA ON RESEARCH INSTITUTIONS, INVESTMENTS, AND IMPACTS

A significant part of the economic literature includes studies that describe, document, and quantify the institutions that fund, regulate, and conduct agricultural research as well as the investments that they make. These "descriptive" studies are of value in their own right, but they also provide an institutional frame of reference and data for econometric and other modeling studies. Although documenting the institutional-descriptive studies alone would take much more time than we can spend in this review, we mention a few key

[10]Over the past several decades in particular, federal government departments and agencies other than agriculture, such as the National Science Foundation, National Institutes of Health, Department of Defense, and the Environmental Protection Agency, account for a larger, and now sizable, share of the federal funds directed to public agricultural R&D in the United States.

[11]de Gorter et al. (1992, p. 30) recognized the issue of multiple governments and asserted that "there is no reason to believe that disaggregating the decision process would refute [their] results." Gordon Rausser has advised us in a personal communication that Rausser et al. (2009) formally demonstrate that, even when agricultural research is the result of policies chosen by different governments, a criterion function can be derived that is based on a weighting of consumer, producer, and taxpayer interests.

[12]Given very long agricultural R&D lags, it does not seem reasonable to use a model that requires an implicit assumption that commodity program policies set in a given farm bill will be fixed for the period in which the R&D policies set in the same farm bill will have effect. For instance, consider the dramatic changes in farm program policies in 1985, 1996, and 2002 (e.g., see Alston & Sumner 2007).

studies that documented institutions in the context of making broader contributions to the literature on the economics of research. Notable contributions to the literature on U.S. agricultural research policy that provided institutional history, documented data on investments, or both include Ruttan (1982), Huffman & Evenson (1993, 2006), Kerr (1987), and Alston & Pardey (1996, 2006). Studies taking an international perspective include Hayami & Ruttan (1971), Evenson & Kislev (1975), Baum (1986), Pardey et al. (1991, 2006), Alston et al. (1999), and World Bank (2008).

Work has also been undertaken to develop concepts and measures related to agricultural science effort (in terms of public and private research investments, training and employment of research staff, and the like) and research output (in terms of new crop varieties and livestock breeds, patents, plant breeders rights, publications, and so on). In addition, substantial investments have been made in conceptual and empirical development of other measures (e.g., of prices and quantities of agricultural inputs and outputs) that are useful for measuring production relationships in agriculture, including research outcomes (e.g., the impacts on prices, production, consumption, and trade as well as the total benefit from research and its distribution).

Studies of the relationship between research and productivity rely on the painstaking and demanding work of the economist who makes the data on inputs and outputs used in studies of production more generally. As noted by Griliches in his Presidential Address to the American Economic Association:

> We ourselves do not put enough emphasis on the value of data and data collection in our training of graduate students and in the reward structure of our profession. It is the preparation skill of the econometric chef that catches the professional eye, not the quality of the raw materials in the meal, or the effort that went into procuring them (Griliches 1994, p. 14).

In his Waugh lecture to the American Agricultural Economics Association, Gardner discussed the importance of data creation and of having econometricians and other data users know how the data they use were created:

> Agricultural economists and other social scientists tend to take data as facts. . . The problem is the data are not facts. Facts are what is really there. Data are quantitative representation of facts, which statistical workers and economists concoct (Gardner 1992, p. 1074).

> I call the study of how primary statistical information is made into economic data "factology." The neglect of factology risks scientific ruin (Gardner 1992, p. 1067).

Gardner drew specific attention to the measurement of agricultural inputs (especially capital), outputs, and productivity as instances where a lot of effort and judgment goes into the creation of the "data," such that the data themselves are very much transformed from the raw material used to make them, and consequently areas where factology matters more than most. The same point applies perhaps even more forcefully to studies of the returns to agricultural R&D, when they 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. Unfortunately, the lessons from Gardner's lecture have not been embraced by all

practitioners, but some progress has been made with developing and documenting improved measures of agricultural inputs, outputs, and productivity as well as agricultural research investments, which are the raw materials for many studies of returns to agricultural R&D.

Andersen (2005) reviewed previous studies of U.S. agricultural productivity patterns and documented the evolution of approaches and results.[13] This literature shows an evolution from national fixed-weight indexes to state-level Divisia approximations using Fisher-ideal or Tornqvist-Theil indices, with increasing use of the appropriate index number theory (and other economic theory) combined with less aggregated data to reduce index number bias and other distortions in the measures.

Two separate long-term endeavors, one led by Eldon Ball at the U.S. Department of Agriculture (USDA)-Economic Research Service 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 and similar basic information (for details and discussion, see Acquaye et al. 2000, 2003; Andersen 2005; Andersen et al. 2008; Alston et al. 2009). The data from Andersen et al. (2009) were developed specifically for measuring the economic consequences of U.S. public agricultural research, and the creation of these and the corresponding data on research investments has been by far the most demanding part of that long-standing project culminating in the book by Alston et al. (2009).

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 relative neglect could be comparatively pernicious. It takes a lot of work to develop measures of agricultural research investments. Appropriate measures of public agricultural research investments are not published in suitably long time series, in the relevant form, by any government agency. However, some data have been compiled by Huffman & Evenson (1993), the National Science Foundation (2008), Robbins & Moylan (2007), and Pardey & Andersen (2009). Guidelines for compiling such data include work by the Organization for Economic Cooperation and Development (2002, 2005). For international data, see Pardey et al. (2006) and the Agricultural Science and Technology Indicators (ASTI) Web site at **http://www.asti.cgiar.org/**.

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 also requires going across places and backward through time, dealing with changing definitions, changing reporting procedures, and inevitable omissions. The long agricultural R&D lags mean

[13]Barton & Cooper (1948), Loomis & Barton (1961), and Baron & Durost (1960) were among the first researchers to compile national indexes of inputs, outputs, and productivity in U.S. agriculture. These authors calculated fixed-weight indexes, where the weights were equal to the average price of each subaggregate over a few selected years (see also Griliches 1960). The USDA published fixed-weight (Laspeyres) indexes of inputs, outputs, and productivity annually in *Changes in Farm Production and Efficiency* until the early 1990s. Griliches & Jorgenson (1966, 1967) were among the first to apply Divisia aggregation procedures to productivity measures of the general economy. According to Capalbo & Vo (1988, p. 101), Brown (1978) was the first researcher to compile Divisia indexes of inputs and outputs in U.S. agriculture. More recent studies of U.S. agricultural productivity include Ball (1985), Evenson et al. (1987), Capalbo & Vo (1988), Craig & Pardey (1990a,b; 2001), Jorgenson & Gollop (1992), Huffman & Evenson (1992, 1993), Ball (1994), Pardey et al. (1994), Ahearn et al. (1998), Ball et al. (1997), Ball & Nehring (1998), Ball et al. (1999), Acquaye et al. (2000, 2003), and Alston et al. (2009).

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 researchers 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, because 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 economics researchers: For compilations of U.S. private sector agricultural R&D data, see Huffman & Evenson (1993), Klotz et al. (1995), Fuglie et al. (1996), Echeverría & Byerlee (2002), and Dehmer et al. (2009).

4. ATTRIBUTION PROBLEMS IN MODELS OF RESEARCH IMPACTS

In modeling the effects of research on agricultural productivity the two principal areas of difficulty are in identifying the research lag structure (the temporal attribution problem) and in the treatment of knowledge spillovers whether they are among different firms within an industry, different industries within a country or other geopolitical entity, or among countries (the spatial and institutional-cum-sectoral attribution problem).

4.1. Temporal Aspects of the R&D Attribution Problem

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

A large number of previous studies have regressed a measure of agricultural production or productivity against variables representing agricultural research and extension, often with a view to estimating the rate of return to research. Alston et al. (2000) provided a comprehensive reporting and evaluation of this literature (see also Schuh & Tollini 1979, Norton & Davis 1981, Evenson 2001, Alston et al. 2009).

Only a few studies have presented much in the way of formal theoretical justification for the particular lag models they have employed in modeling returns to agricultural research. Alston et al. (1995) presented a conceptual framework based on a view that agricultural production uses service flows from a stock of knowledge (e.g., see Rausser 1974), which is augmented by research (e.g., see Griliches 1979).[14] The specification of the determinants of the lag relationship between research investments and

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

production, which involves the dynamics of knowledge creation, depreciation, and utilization, is crucial. A finite lag distribution relates past investments in research to current increments to the stock of knowledge. However, even if knowledge depreciates in some fashion over time, under reasonable views of the nature, rate, and form of depreciation of knowledge, some effects of research will persist forever. As a practical matter, analysts end up representing these effects with a finite distributed lag that represents the confounded effects of the lags in the knowledge creation process and the dynamics of depreciation of the knowledge stock. In such a context, it is difficult to have precise views about the nature of the reduced-form empirical lag relationship between research investments and productivity, in terms of its overall length and shape, apart perhaps 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.

Table 2 summarizes some key features of research lag distribution models applied in studies of agricultural productivity in Organization for Economic Cooperation and Development countries. This table represents a reworked version of table 5 in Alston et al. (2000). Until quite recently, it was common to restrict the lag length to be less than 20 years. In the earliest studies, available time series were short and lag lengths were very short, but the more recent studies have tended to use longer lags. Most studies have restricted the lag distribution to be represented by a small number of parameters, both because the time span of the data set is usually not much longer than the assumed maximum lag length and because the individual lag parameter estimates are unstable and imprecise given the high degree of collinearity between multiple series of lagged research expenditures.[15]

In their application using long-run, state-level data on U.S. agriculture, Alston et al. (2009) found in favor of a gamma lag distribution model with a much longer research lag than most previous studies had found—for both theoretical and empirical reasons.[16] 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. Alston et al. (2008) also documented the adoption lags for particular agricultural technologies and their results are consistent with relatively long overall lags. This comparatively long lag has implications for both econometric estimates of the effects of research on productivity and the implied rate of return to research.

4.2. Spatial Aspects of the R&D Attribution Problem

Compared with the research lag structure, the issue of spatial attribution has received less attention in the literature on agricultural R&D and has been approached differently in the

[15]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 & Adams 2002, Thirtle & Bottomley 1988), and trapezoidal (e.g., Huffman & Evenson 1989, 1992, 1993, 2006; Evenson 1996). A small number of studies have used free-form lags (e.g., Ravenscraft & Scherer 1982, Pardey & Craig 1989, Chavas & Cox 1992).

[16]The detailed arguments are laid out in Alston et al. (1995) and some earlier evidence is presented by Pardey & Craig (1989) and Alston et al. (1998) (see also Huffman & Evenson 1989). Alston et al. (1998) discussed the issue of knowledge depreciation drawing on the previous literature, and these arguments are restated and refined by Alston et al. (2008), and Alston et al. (2009).

Table 2 Research lag structures in studies of agricultural productivity[a]

Characteristic	Number of estimates	1958–1969	1970–1979	1980–1989	1990–1998	1958–1998
	Count	Percentage				
Research lag length (benefits)						
0–10 years	253	9.7	6.2	17.9	12.7	13.4
11–20 years	537	41.9	22.0	38.8	22.8	28.5
21–30 years	376	0.0	20.7	12.0	25.9	19.9
31–40 years	178	0.0	4.3	5.6	14.3	9.4
40 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[b]	109	12.9	13.1	3.2	4.9	5.8
Unclear[c]	190	0.0	16.7	12.7	6.3	10.1
Total	1,886	100.0	100.0	100.0	100.0	100.0

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

literature on industrial R&D. In the more-recent literature, however, increasing attention has been paid to accounting for the fact that knowledge created within a particular geopolitical entity can have impacts on technology elsewhere, with implications that may matter to both the creators of the spillouts and the recipients of the spillins (for a review of this literature, see Alston 2002).

Some of the earliest work on these matters was done in applications to agriculture. The analysis by Griliches (1957) of the generation and dissemination of hybrid-corn technology throughout the United States was a seminal study in the economics of diffusion as well as the spatial spillover of an agricultural technology. This work inspired others on adoption of individual technologies, some of which entailed spatial spillovers. For example, Evenson & Kislev (1973) analyzed spillovers related to wheat and maize research, Araji et al. (1995) looked at spillovers regarding potato research, and Maredia et al. (1996) and Traxler & 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.

Other studies have sought to assess the overall effects of agricultural research on productivity, including spillover impacts, with regression-based methods using more aggregate (region- or state-specific as well as national) measures of R&D. For example Huffman & 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.

Whether they were concerned with spillovers or not, the past studies have imposed implicit or explicit assumptions about the spatial spillover effects of agricultural research based on geopolitical boundaries. For example, most past studies of the effects of U.S. agricultural research on productivity have implicitly assumed that agricultural research is totally fungible, such that U.S. national agricultural output depends on the national aggregate of U.S. spending on public agricultural R&D, regardless of where it was spent or by whom (e.g., Griliches 1964, Evenson 1967, White & Havlicek 1982, Chavas & Cox 1992, Alston et al. 1998). In contrast, some studies at the level of individual states proposed that research efforts by individual states have spillover effects only among states within the same (subnational) geopolitical region, whereas research outside a region does not affect its agricultural productivity (e.g., Khanna et al. 1994, Yee & Huffman 2001).[17] Several other studies, beginning with Huffman & Evenson (1989), incorporated geoclimatic information while retaining the restriction that technology spillovers occur only among neighboring states within contiguous geopolitical regions. Huffman & Evenson (1992, 1993, 2001, 2006), Huffman & Just (1994, 1999), and McCunn & Huffman (2000) subsequently used the same set of constructed spillover weights.

Many studies, however, simply ignored the effects of research in other states or by the federal government, and almost all of the regression-based studies of agricultural R&D have ignored the possibility of international spillovers, unless they were specifically emphasizing that possibility.[18] Looking more broadly at the literature, few studies of national systems, irrespective of the method used, have allowed for either spillins or spillouts—in their meta-analysis, Alston et al. (2000) identified less than 20% of studies allowing for any spillovers.

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

5. EVIDENCE ON THE ECONOMIC CONSEQUENCES OF AGRICULTURAL R&D

Alston et al. (2000) conducted a meta-analysis of 292 studies that reported estimates of returns to agricultural R&D, and they reported an overall mean internal rate of return for their sample of 1852 estimates of 81.3% with a mode of 40% and a median of 44.3% (see **Table 3**). After dropping some outliers and incomplete observations, they conducted regression analysis using a sample of 1128 estimates with a mean of 64.6%, a

[17]Citation patterns in the patent applications and in professional published literature indicate that spatial spillovers are much more pervasive.

[18]Bouchet et al. (1989) is an exception. In addition, studies of the effects of the CGIAR centers on agricultural productivity in adopting countries using other than regression methods have emphasized the spillins of technology (e.g., Brennan & Fox 1995, Pardey et al. 1996, Brennan et al. 1997, Brennan & Bantilan 1999, Brennan 2007). Alston (2002) reviewed these studies. Brennan (2007) reported a more-recent application to wheat spillovers from CIMMYT to Australia.

Table 3 Lag structures and rates of return to agricultural R&D[a]

Characteristic	Estimates		Rate of return				
	Number	Share of total	Mean	Mode	Median	Minimum	Maximum
	Count		Percentage				
Research lag length							
0–10	370	20.9	90.7	58.0	56.0	−56.6	1,219.0
11–20	490	27.7	58.5	49.0	43.7	−100.0	677.0
21–30	358	20.2	152.4	57.0	53.9	0.0	5,645.0
31–40	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

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

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.

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

5.1. Recent Evidence on U.S. Agricultural R&D

More recently, Alston et al. (2009) modeled 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. (2000) and emphasized in this section, in particular to modeling the research lag distribution and the state-to-state spillovers of research impacts. Spillovers (or agroecological similarity or technological closeness) between states were represented using a measure based on output mix correlations—an adaptation of the approach of Jaffe (1986, 1989) who constructed a measure of technological distance between firms based on patent data. 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 because state governments may be expected to ignore or at least (heavily) discount the spillover benefits to other states.

Table 4 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.[19] 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

[19]There are compelling reasons to report benefit-cost ratios rather than internal rates of return in this instance, as discussed by Alston et al. (2009). Some internal rates of return are reported here to facilitate comparisons with other studies.

Table 4 Benefit-cost ratios and internal rates of return for U.S. agricultural R&D[a]

Returns to	Benefit-cost ratio (3% real discount rate)		Internal rate of return	
	Own-state	National	Own-state	National
State research and extension	Ratio		Percent per year	
48 states				
Average	21.0	32.1	18.9	22.7
Minimum	2.4	9.9	7.4	15.3
Maximum	57.8	69.2	27.6	29.1
Selected states				
California	33.3	43.4	24.1	26.1
Minnesota	40.6	55.4	24.7	27.3
Wyoming	12.7	23.6	16.8	20.9
Regions				
Pacific	21.8	32.9	20.2	23.5
Mountain	20.0	31.6	19.0	22.7
Northern Plains	42.4	54.5	24.9	27.0
Southern 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

[a]Source: Alston et al. (2009).

$32 across the states. The marginal benefit-cost ratio for USDA intramural research was comparable, at $18 per dollar invested in research.

The benefit-cost ratios in **Table 4** 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. (2000) and summarized in **Table 3**, and as discussed by others (e.g., Evenson 2001, Fuglie & 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, 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.

6. CONCLUSION

The literature on the economics of agricultural R&D is large. In this review, we have concentrated on some key areas where results may be fragile or distorted as a result of modeling choices made by economists. The creation of the "data" used in our analyses is a critical step. Because 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. Like the work of creating data, factology is not well rewarded within the agricultural economics profession. Even so, the available data have significantly improved as a result of the efforts of a few individuals.

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 modeling 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 they can have substantial impacts on the findings. The issue of how to go about specifying the research-induced technical change 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 relatively important effects on estimates of the distribution of benefits and relatively little effect on estimates of the total benefits.

Agricultural economists have invested extensively in quantifying the payoffs to agricultural R&D, but for the most part, these studies have referred to total benefits to the relevant society, rather than to particular groups in society. Partly, this may reflect the fact that findings regarding distributional impacts are comparatively sensitive to aspects of specification that often must be chosen arbitrarily; thus the results are fragile. An example is Cochrane's technology treadmill argument suggesting that, among farmers, only the early adopters of new technology benefit, and even they do so only temporarily (Cochrane 1958, Herdt & Cochrane 1966). As shown in this review, specific conditions must hold for this argument to be true (it requires a relatively inelastic demand and a multiplicative supply shift), and they probably do not hold in most applications.[20] But what we do not have is compelling, direct econometric evidence to show that farmers have in fact benefited from technological change. It says something about our models and measures that we have not yet been able to address this issue definitively.

As a profession, we have amassed a persuasive body of evidence demonstrating that the world as a whole and individual nations alone have benefited enormously from productivity growth in agriculture, a substantial amount of which has been enabled by technological

[20]Even considering agriculture in aggregate in the United States, the relevant demand is likely to be quite elastic (see Alston 2007), which is sufficient for farmers to benefit, even if research causes a multiplicative supply shift, for which there is no evidence. For any individual agricultural industry for any individual country, demand is likely to be highly elastic because of international trade. The relevant demand is likely to be highly inelastic in a case where the analysis applies to relative aggregated commodities in the world as a whole—e.g., global producer benefits from increases in the supply of wheat—or highly localized markets in a developing country where lack of adequate infrastructure circumscribes the market reach of agricultural producers.

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 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. An implication is that the substantial government intervention notwithstanding, the world is continuing to underinvest in agricultural R&D.

SUMMARY POINTS

1. The total gross annual research benefits depend primarily on the size of the research-induced supply shift and the scale of the industry to which it applies.
2. The distribution of the benefits between producers and consumers depends on the relative elasticities of supply and demand, on the nature of the research-induced supply shift, and, less importantly, on the functional forms of supply and demand.
3. The very specification of technology defined at the industry level or the use of a representative firm model will condition distributional results. If simple models (such as the Cobb-Douglas model or the Constant Elasticity of Substitution model) are used to represent the production function, then factor-augmenting technological change—whether neutral across all factors or biased to augment just one factor—or the inclusion of research as a separate input will imply proportional (pivotal or otherwise divergent) supply curve shifts.
4. The possibility of losses to producers in aggregate as a consequence of research-induced technical change is often discounted, on the grounds either that demand is relatively elastic or that a parallel research-induced supply shift is relatively likely (or that the pivotal shift seems comparatively unlikely), but concrete empirical evidence on that issue has been elusive to date.
5. Models of research benefits have been extended to incorporate various types of market distortions, such as farm commodity programs or trade barriers, the exercise of market power by middlemen, and those resulting from environmental externalities. 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.
6. A significant part of the economic literature includes studies that describe, document, and quantify the institutions that fund, regulate, and conduct agricultural research as well as the investments that they make. These "descriptive" studies are of value in their own right but they also provide an institutional frame of reference and data for econometric and other modeling studies.
7. In modeling the effects of research on agricultural productivity, the two principal areas of difficulty are in identifying the research lag structure (the temporal attribution problem) and in the treatment of knowledge spillovers whether they are among different firms within an industry, among different industries within a

country or other geopolitical entity, or among countries (the spatial and institutional-cum-sectoral attribution problem).

8. A predominant and persistent finding across the economic returns-to-research studies is that the measured rate of return is quite large. The main mass of the distribution of internal rates of return reported in the literature is between 20% and 80% per annum.

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