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Reflections on Agricultural R&D, Productivity, and the Data Constraint: Unfinished Business, Unsettled Issues

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ABSTRACT. Sixty years ago, T.W. Schultz introduced the idea of the productivity "residual" to agricultural economics. His main message was that growth in conventional inputs accounted for little of the observed growth in agricultural output, and that there was work to be done by agricultural economists to understand and ultimately eliminate this unexplained residual called "productivity." Thus was launched the economics of agricultural productivity as a sub-field within agricultural economics, along with the economics of agricultural R&D and innovation and related government policy. Much progress has been made in the decades since. Still, critical issues remain unresolved. This matters because agricultural innovation and productivity matter, and so do the related policies that rest to some extent on our established understanding of the economic relationships. In this paper, I review some unsettled issues related to economic models and measures applied to agricultural R&D and productivity, and some unfinished business in terms of economic and policy questions that are not yet well answered. Before doing that, I present some evidence on agricultural productivity and why it matters. Next, with a nod to "factology," I present available productivity measures from USDA and InSTePP, and compare them in the context of translog cost function models. In subsequent sections I use these and other data to develop new evidence related to two contentious questions: (1) Do farmers benefit from public agricultural R&D? (2) Has U.S. agricultural productivity growth slowed in recent decades? The answers are revealed within.

1. Introduction

Sixty years ago, T.W. Schultz (1956) introduced the idea of the productivity "residual" to agricultural economics. The main message in that seminal paper was that growth in conventional inputs accounted for little of the observed growth in agricultural output, and that there was work to be done by agricultural economists to understand and ultimately eliminate this unexplained residual called "productivity." Schultz and his student Zvi Griliches (1963) made initial inroads into this task, identifying improvements in quality of inputs, including education of farmers, and changes in technology as major sources of productivity growth—attributable ultimately to investments in science, education and formal and informal R&D by individuals, firms and governments.

Thus was launched the economics of agricultural productivity as a sub-field within agricultural economics, along with the economics of agricultural R&D and innovation and related government policy. Much progress has been made in the decades since, elaborating on the ideas presented by Schultz and Griliches (in the works cited above and others) and refining the concepts as well as improving the methods of measurement and the measures. Still, critical issues remain unresolved; much is in dispute, and in many aspects the evidence is unconvincing or the state of the art is otherwise unsatisfactory. This matters because agricultural innovation and productivity matter, and so do the related policies that rest to some extent on our established understanding of the economic relationships.

The economic policy stakes are large. Agricultural innovation, increasingly driven by organized agricultural R&D, has served as an engine of economic progress, priming the pump of the agricultural transformation that has been an integral element of economic progress around the world. But incentives are weak and attenuated in many areas of agricultural R&D, leaving a crucial role for governments to play both in establishing the institutions that encourage private innovation, including investments in R&D, and in filling the gaps that remain by funding public investments in socially valuable research areas that the private sector nevertheless neglects.

Evidence of remarkably high sustained rates of social payoffs to both private and public investments in agricultural R&D testify to a significant failure of government to fully address the underinvestment problems caused by the market failure. Moreover, unfortunately, if anything, in the high-income countries like the United States, agricultural R&D policies seem to be trending in the wrong direction, making matters worse. Is this to some extent our fault—a failure of the profession to provide enough of the right types of evidence and ideas at the right time to enable better policies to be made? Or is it simply a reflection of the limited role of economic evidence in policymaking—especially as it applies to global public goods like agricultural science and climate change, where the lags between action and outcome are extremely long and variable, the benefits are diffuse, and much uncertainty surrounds who precisely will benefit, when, and by how much.

In what follows I review some unsettled (and perhaps unsettling) issues related to economic models and measures applied to agricultural R&D and productivity, and some (to some extent consequently) unfinished business in terms of economic and policy questions that are not yet well answered. Before doing that, I present some evidence on agricultural productivity and why it matters.

2. Productivity Matters (and the Agricultural R&D Policy Paradox)

Over the past half-century, while the world's population more than doubled the quantity and real value of agricultural output more than trebled, even though land in agriculture increased by only about one-tenth, making for an era of unprecedented agricultural abundance (Alston and Pardey 2014). This remarkable accomplishment belied widespread prophecies of doom in the early 1960s, coming from a perspective—based on traditional agriculture and conventional inputs—that did not anticipate the transformation of agriculture that was to come soon after for large parts of the world. Investments in agricultural science and technology and other "nontraditional" inputs such as knowledge and education, and improvements in the quality of material inputs and people, played a crucial role, helping to shift agriculture to a firmer footing and capitalize on agriculture as an engine of economic growth (Timmer, 2009; Alston and Pardey 2014, 2017).

The experience of the United States illustrates the value of farm productivity growth in the context of the agricultural transition. In 1916, the U.S. farm population peaked at 32.5 million, 31.9 percent of the total U.S. population. Since then, while the U.S. population continued to grow, the farm population declined to an estimated 4.6 million in 2013, just 1.5 percent of the total. A dramatic transformation of agriculture, with farms becoming much larger (and symmetrically many fewer) and more specialized, was achieved through the progressive introduction and adoption of a host of technological innovations and other farming improvements that enabled much more to be produced with less land and a lot less labor. Productivity grew rapidly. For example, Schultz (1956, p. 753) wrote:

> From 1923 to 1929 only about one-half—or a little more—of the increase in output appears to have been achieved by additional inputs. During the depression years, 1930 to 1940, none of the increase in output seems to be explained by additional inputs. … The war years called forth substantially more output, yet from 1940 to 1948 perhaps only a fifth to a fourth of the increase in output can be explained by additional inputs.

The same phenomenon continued over the next 60 years, as U.S. farm output more than doubled in spite of reductions in land and especially labor employed in agricultural production. Specifically, during the period 1949–2007 the InSTePP (Pardey et al. 2009) index of U.S. farm output (*Q*) increased from 100 to 269, but none of this increase can be explained by increases in inputs (adjusted for compositional changes) because the index of aggregate inputs (*X*) actually fell from 100 to 96 such that the index of multifactor productivity ($MFP = Q/X$) grew from 100 to 280.[1] Hence, the unexplained differential between output growth and input growth called "productivity growth" accounts for *more than* 100 percent of the postwar increase in U.S. farm output.[2]

[Figure 1: Inputs, outputs and MFP in U.S. agriculture, 1949–2007]

Clearly agricultural productivity growth is enormously valuable. Of the actual farm output in 2007, worth about $330 billion, only one-third (i.e., 100/280 = 0.36) or about $118 billion could be accounted for by conventional inputs using 1949 technology, holding productivity constant. The remaining two-thirds (i.e., 180/280 = 0.64) or about $212 billion in that year alone is attributable to the factors that gave rise to a 180 percent increase in

[1] Pardey et al. (2009) describe the University of Minnesota's InSTePP (International Science and Technology Practice and Policy center) Production Accounts, Version 5 (available at www.instepp.umn.edu/united-states).

[2] If, instead of falling, inputs had been held constant at the 1949 quantities, output would have increased by a factor of 2.8:1 instead of 2.7:1.

productivity since 1949—including improvements in infrastructure and inputs (if not captured already in the indexes), as well as new technology, developed and adopted as a result of agricultural research and extension, and other sources of innovations.

Another way to look at this counterfactual is in terms of the quantities of inputs that would be required to produce the 2007 quantity of output (2.7 times the 1949 output) using 1949 technology (i.e., productivity and factor shares): i.e., 2.7 times the 1949 quantities.[3] An increase to 2.7 times the actual quantities of land and labor (along with capital and other inputs) used in 1949 would require adding 2.0 billion acres (an area the size of the contiguous United States or Australia, much more than the total agricultural area in either country) to the 1949 quantity of land used in agriculture, and an additional 34 billion hours of operator, family and hired labor (or about 12 million FTEs); the required increase would be closer to 2.5 billion acres over the 2007 quantity of land and a fivefold increase over the 2007 farm labor force! That these required increases seem absurd speaks to the remarkable "productivity" performance and the transformation of U.S. agriculture in the second half of the 20th century.

Available evidence from much study of the subject indicates that a very large (and probably increasing) share of U.S. agricultural productivity growth is attributable to organized agricultural science—whether conducted in the private sector or the public sector. The annual value of farm productivity growth is large, as we have seen, both in absolute terms and relative to the annual investment in farm productivity-enhancing R&D. Partly for that reason, the

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[3] An alternative measure is 2.8 times the actual quantities of land, labor, capital and other inputs used in 2007 (i.e., using 2007 factor shares), which would be less dramatic but nonetheless striking. Neither of these counterfactuals is entirely reasonable or ideal for our purposes.

returns to those investments have been very favorable (see, e.g., the review by Hurley et al. 2016), indicating a systematic sustained pattern of underinvestment from the point of view of society as a whole (see, e.g., Rao et al. 2016).

These main claims are not in dispute (although some economists working in the area may disagree with one another about specific aspects of the measures of research returns and their intepretation). Remarkably, nevertheless, during the 21st century in real terms U.S. public funding for agricultural and food R&D has stalled and more recently shrunk and, within this now shrinking agricultural and food R&D portfolio, the balance has shifted away from farm productivity-enhancing R&D (see, e.g., Pardey, Alston and Chan-Kang 2013; Clancy, Fuglie and Heisey, 2016). The U.S. government does not show any sign of reversing those trends; an exacerbation seems more likely.

It appears to be widely understood that *market failure* is widespread in the context of agricultural science and technology. It may be less well understood that governments have not done nearly enough to address the consequences of these market failures; that *government failure* is also widespread in this context. Agricultural economists have invested a great deal in modeling and measuring the social costs of government failure to choose farm subsidy policies or agricultural trade policies that will maximize national economic surplus; very little, by comparison, has been done on analyzing and measuring the social cost of government failure in agricultural R&D policy. But the size of the economic losses from poor agricultural R&D policy decisions may be orders of magnitude greater than the losses from the much more extensively quantified distortions from farm commodity policies (trade policies and other farm subsidies).

In an analysis of policies as they applied in 2006, for example, I estimated that, for every dollar of U.S. government spending on farm subsidies, farmers received about 50 cents, landlords received about 25 cents, domestic and foreign consumers received about 20 cents, and 5 cents was wasted (see Alston 2009). Additional amounts are wasted collecting the taxes to finance the spending and in administering the policies—costing taxpayers perhaps another 20 cents per dollar. By these measures eliminating expenditure on farm programs of $20 billion (with a social opportunity cost of, say, $24 billion) would cost farmers $10 billion and would avert a net social cost of $1 billion (or $5 billion if we count the social opportunity cost of the funds). In contrast, agricultural research involves a "deadweight gain."

Our estimates (Alston et al. 2010, 2011) indicate that U.S. federal and state government expenditure on agricultural research and extension generates benefit-cost ratios of at least 10:1 (more likely 20:1 or 30:1)—evidence of a serious underinvestment. Pardey and Beddow (2017), echoing Pardey, Alston and Chan-Kang (2013) suggested that a reasonable first step would be to double U.S. public investment in agricultural R&D—an increase of, say, $4 billion over recent annual expenditures.[4] A conservatively low benefit-cost ratio of 10:1 implies that having failed to spend that additional $4 billion per year on public agricultural R&D imposes a net social cost of $36 billion per year—an order of magnitude greater than the annual $1–5 billion social cost of $20 billion in farm subsidies.

[4] Compilations of estimates of public and private spending on agricultural and food R&D in the United States are available from the USDA (see, e.g., Fuglie and Toole 2014) and InSTePP (see, e.g., Pardey, Alston and Chan-Kang 2013). Either source would support an estimate of public spending of a bit over $4 billion in recent years (roughly one-third of the total public and private spending on agricultural and food R&D).

These rough calculations are crude but plausible in view of the value of productivity growth and the role of R&D in driving it, and the compelling evidence of sustained high rates of return to R&D. We can quibble about whether the benefit-cost ratio would be so large for such a large increase, and how such an increase might have to be phased in over time to allow for developing the capacity to spend the funds well and wisely; but anyone who has doubts about the scale of the potential benefits relative to the expenditures is advised to consider the scale of the past benefits attributable to farm productivity growth and the implications of an absence of that growth for either massive output reductions or huge additional resource requirements to sustain production. Perhaps this topic deserves more attention from economists interested in the social costs of distortions in agricultural policy—including those that reflect errors of omission (as in agricultural R&D) as well as commission (as in subsidies).

Here endeth my attempt to provide a motivation for an interest in the economics of agricultural R&D and productivity and the related policy, and for some concern over whether we are getting the relevant concepts and measures right. What follows is a selective (and somewhat self-serving) sampling of some unsettled issues among economists and some unfinished business in economics research related to agricultural R&D and productivity and related policy. A discussion of factology is a good place to start.

3. Factology and Productivity Measures

Twenty-five years ago, in his Fellow's Lecture to this Association, Bruce Gardner (1992) discussed the importance of data creation and of having econometricians, policy analysts 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 (p. 1074)
>
> I call the study of how primary statistical information is made into economic data "factology." The neglect of factology risks scientific ruin (p. 1067).

Factology is important in the context of the measurement of agricultural inputs, outputs, and productivity, a context where analysts in constructing the "data" make a great many choices that can matter much for the measures and their interpretation. As Gardner (1992, p. 1071) noted specifically in the context of productivity measures:

> For data that themselves tell a story, and a different story depending on the use to which the data are to be put, it is especially important for the user to undertake an investigation in factology before telling the story.

In his Presidential Address to the American Economic Association, Zvi Griliches (1994, p. 2) made some similar points, with specific reference to productivity measurement:

> [We] often misinterpret the available data because of inadequate attention to how they are produced and that same inattention by us to the sources of our data helps explain why progress [in understanding the sources of productivity growth] is so slow… . Great advances have been made in theory and in econometric techniques, but these will be wasted unless they are applied to the right data.

Available measures of U.S. agricultural inputs, outputs, and productivity and their evolution illustrate the issues well. The USDA Economic Research Service (USDA-ERS) has played a longstanding role, led well by Eldon Ball for many years, in developing measures of U.S. agricultural productivity. As discussed by Gardner et al. (1980), and Shumway et al. (2014, 2016) in the most recent episodic external review of that activity, these measures have certainly come a long way in terms of addressing the conceptual and measurement issues raised by Schultz and Griliches. Since the early 1980s, a parallel project has been underway at the University of Minnesota, led by Philip Pardey and, since 2003, conducted under the auspices of the International Science and Technology Practice and Policy (InSTePP) Center (see, e.g., Pardey and Craig 1989). The two projects have evolved in parallel, to some extent competitively, with mutual learning and improvement in both and some convergence over the course of more than a quarter of a century. Today, a researcher can download annual series of state-specific and national indexes of prices and quantities of inputs and outputs, and productivity, from either InSTePP (2009) for the years 1949–2007 or the USDA (2015) for the years 1948–2013 (only 1960–2004 for state-specific).[5] Which should we use? Does it matter?[6] How should we decide?

As discussed by Andersen et al. (2011), and earlier by Acquaye et al. (2003), the two sets of measures have much in common in terms of their methodological underpinnings and data sources. Both sets of estimates apply the same index number theory and use discrete approximations to Divisia indexes, and both begin with highly disaggregated inputs and outputs to reduce the effects of pre-aggregation bias. But they also entail some notable differences in methods that give rise to some meaningful differences in indexes that ostensibly measure the same conceptual quantity—and more so for some states than for the national indexes. Andersen et al. (2011) identified differences in capital as being comparatively important.

[5] The USDA data (1948–2013) are available at https://www.ers.usda.gov/data-products/agricultural-productivity-in-the-us/agricultural-productivity-in-the-us/#National Tables, 1948–2013, and the InSTePP data (1949–2007) are available at http://www.instepp.umn.edu/united-states#Version 5.

[6] In reviewing the USDA-ERS data, Shumway et al. (2016) paid remarkably little attention to the existence of the alternative, InSTePP data, the differences between the two data sets, and what to make of the differences.

Certainly, their plots of InSTePP versus USDA data tell very different stories about capital use in U.S. agriculture over the second half of the 20th century. Andersen et al. (2011) showed these differences could be attributed largely to the use of the annually variable versus fixed interest rates in the computation of capital service flows, and they argued in favor of the fixed interest rate approach as used by InSTePP both on conceptual grounds and because the resulting measures appeared more sensible. The differences remain interesting regardless of which approach we might prefer in principle—perhaps more so if we are not sure.

Many studies use one of these datasets or the other without apparent regard to fragility from this source, and perhaps without any attention to factology. Andersen et al. (2011) identified numerous examples of studies that utilized the USDA data in a variety of applications, noting that the results from those studies that focused on input use may be especially contingent on the measures of capital service flows. To illustrate these possibilities, Table 1 reports results from estimating a Translog cost function model using the national annual data from the two data sets for the years for which both were available, 1949–2007.[7] The models were estimated subject to the conventional homogeneity and symmetry restrictions and, less conventionally, imposing constant returns to scale at the level of the industry, U.S. agriculture, as a whole.[8]

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[7] Jarrett Hart did the main work of estimating these models, under my direction. These estimates are not meant to be treated too seriously as such—the models were not estimated with that intention and not were subjected to appropriate elaboration and testing—but are provided merely to illustrate how results based on just one of these datasets might be fragile from this perspective.

[8] In evaluating the results from these estimations, I noticed that the USDA-ERS price index for services from land is remarkably volatile, dropping from 1.05 in 1996 to 0.16 in 2000 and 0.12 in 2002 before jumping to 1.35 in 2004. These land rental price gyrations have significant (and seemingly implausible) implications for both the observed and predicted cost share of land (including some negative predicted values from the Translog model) and could

[Table 1: Cost function models applied to U.S. agriculture, 1949–2007]

The two datasets imply quite different estimates for the rates of factor-neutral technical change (twice as fast using the InSTePP data compared with the USDA data), and some substantive differences in the detail of the pattern of factor-biased technical change (though both indicate that technical change has been land-, labor-, and capital-saving, and "other inputs"-using, consistent with the gross trends in factor shares). Perhaps the most significant difference is with respect to the elasticities of factor demand (and corresponding elasticities of substitution). The estimates based on the USDA data imply a (statistically significantly) positive value for the Hicksian (i.e., output constant) own-price elasticity of demand for capital at the mean vector of predicted input shares, which is not consistent with the underlying theory. The other elasticities are largely comparable between the two sets of estimates: the other own-price elasticities are all plausible (and similar); the cross-price elasticities are mostly positive, indicating Hicksian substitutes, but the estimates using the USDA data suggest that capital is a complement for both labor and "other" inputs while the estimates using the InSTePP data suggest that capital and land are complements.

It is not entirely surprising to see capital featured in the differences in elasticities given the observation that the most important difference between the two datasets is in the capital series (as noted by Acquaye et al. 2003 and Andersen et al. 2011). These findings confirm the suggestion by Gardner (1992) echoed by Andersen et al. (2011) that differences in decisions

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well have influenced the cost-function estimation results and other analysis using these data. This feature of the land price index appears to be attributable to the practice of treating land as the residual claimant, for the purpose of computing factor payments to land. In their review of the USDA-ERS data Shumway et al. (2014, 2016) discussed (and largely endorsed) this approach, but do not appear to have noticed its implications for the measures.

about data construction—in the context of measures of agricultural inputs, outputs, and productivity—can have consequences for the inferences drawn from studies that use the data, whether largely untransformed (as in computing productivity measures or other descriptive use) or with more complicated transformations (as in estimating a Translog cost function model and the implied elasticities of factor demand or rates of technical change). We cannot say the Translog model is the right model or that we have shown that the InSTePP measure of capital is better constructed, though given the use of that model the results would seem to favor using the InSTePP data.[9]

In what follows we will revisit this issue—about which dataset to use and how it affects findings—in the context of other unsettled issues and other unfinished business. Among the unsettled issues is whether farmers benefit from agricultural R&D in the long run. Some of us may think we know the answer to this question, but I am not sure we even know how to ask it. To some extent the answer may turn on the quality of the "data" available but some of the issues are conceptual. The same is true of some other unsettled questions related to measures of returns to research and whether productivity growth has slowed. This is a large and diverse agenda, and some of it will get only brief attention here.

4. Who Benefits from Agricultural R&D?

A few years ago, colleagues and I wrote an article for the *Annual Review of Resource Economics* (Alston et al. 2009) in which we briefly summarized a decades-long discussion over

[9] In preliminary analysis, applying the same approach but with a Generalized Leontief model instead of a Translog model yielded a different pattern of differences in results; generally less satisfactory estimates with both datasets.

the determinants of the total benefits from agricultural R&D and the distribution of benefits between producers and consumers. In the conclusion, we noted that in spite of all that work, compelling evidence has not been developed to show whether farmers benefit from technological change in agriculture. This is serious unfinished business.

In the conventional model, research causes the supply curve for agricultural output 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 total gross annual research benefits (GARB) depend primarily on the size of the research-induced supply shift and the scale of the industry to which it applies. 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. Specifically, producers are assured of benefits from vertically parallel supply shifts but they may lose from pivotal supply shifts, depending on the elasticities. In particular, producers do not benefit from a pivotal shift unless demand is elastic.

The possibility of losses to producers in aggregate is often discounted, on the grounds either that demand is relatively elastic (which is valid in some contexts) or that a parallel research-induced supply shift is relatively likely (or that a pivotal shift seems comparatively unlikely), but concrete empirical evidence 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. Further distributional issues are 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? In particular, how is the total producer incidence (benefits or costs) distributed between "farmers" (as the suppliers of land, family labor, and managerial inputs used in agricultural production) and "others" (as the suppliers of inputs purchased by farmers, including hired labor, and other agribusiness inputs used in activities beyond the farm gate).

We can contemplate and potentially measure these outcomes using a variant of the Muth (1965) two-factor, single-commodity market model in which research gives rise to factor-augmenting changes in technology, which imply shifts in factor demand and product supply. Here, benefits to farmers correspond to producer surplus measured off the supply function for the factor(s) supplied by farmers and, under the maintained assumption of competition, total benefits are given by the sum of changes in producer surplus across factor suppliers plus consumer surplus in the output market. In this context, farmers stand to benefit from technological change if it causes an increase in demand for the factors they supply, and thus an increase in expenditure on them.

Using the solution to the Muth model in Alston, Norton and Pardey (1995, pp. 256–264), and interpreting factor X_2 as representing inputs supplied by farmers (and X_1, all inputs purchased by farmers), the proportional rate of change (denoted by E) in expenditure on inputs supplied by farmers (R_2) (or income accruing to farmers from farming) as a function of the rates of factor neutral and X_2-saving technological change, δ and γ, respectively, is given by:

$$(1)\quad \mathrm{E}(R_2) = -\frac{1}{D}(1+\epsilon_2)\left[(\sigma+\epsilon_1)(1-\eta)\delta + \left(\frac{1-s_2}{s_2}\right)\sigma(\epsilon_1+\eta)\gamma\right],$$

where ϵ_i denotes the supply elasticity for factor i, σ denotes the elasticity of factor substitution, η denotes the absolute value of the elasticity of demand for the final product, s_2 represents expenditure on inputs supplied by farmers ($s_1 = 1 - s_2$ for other inputs) as a share of total expenditure (or total gross farm income), and $D = \sigma(\eta + s_1\epsilon_1 + s_2\epsilon_2) + \eta(s_2\epsilon_1 + s_1\epsilon_2) + \epsilon_1\epsilon_2 > 0$.[10] Since all of the parameters are defined as positive magnitudes E(R_2) is unambiguously negative if demand is inelastic ($\eta < 1$)—farmers are made worse off by both neutral technical change and X_2-(farmer-supplied inputs)-saving technical change. If demand for farm output is elastic ($\eta > 1$), however, the sign of equation (1) is ambiguous—farmers are still made worse off by X_2-saving technical change but they benefit from neutral technical change, and the net outcome depends on the relative importance of the two types of technological change.[11]

Consider the case of U.S. agriculture. Is demand for aggregate U.S farm output inelastic? Has innovation been predominantly either factor-neutral or biased in the direction of saving land, labor and other inputs supplied by farmers? If the answer to both questions is yes, then we would expect to have seen a shrinking in payments to farmers after adjustment for the effects of population and income growth and other demand-side factors on the demand for

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[10] I opted to interpret the factor-saving technological change as applying to inputs supplied by farmers since major innovations have involved labor-saving and land-saving technologies, and land and labor are the principal inputs supplied by farmers. R_2 corresponds to net farm income, in that it represents the remainder after payments for purchased inputs, which goes to pay for inputs supplied by farmers. The corresponding net welfare measure would be producer surplus measured off the supply function for inputs supplied by farmers, X_2, which will increase with increases in R_2 in this analysis.

[11] To see why, suppose the demand elasticity is constant and exactly unitary. In this case, the total expenditure on all inputs will be constant, regardless of their productivity and total production, and consequently farmers will necessarily lose when technological changes cause a reduction in the factor share of the inputs they supply. In contrast, if demand is inelastic, total expenditure on all inputs will shrink when average and marginal costs fall, exacerbating the effect of factor-biased technological changes on reducing the demand for land and labor supplied by farmers. Only when demand is elastic can farmers expect to benefit from factor-neutral changes in farming technology, and demand has to be even more elastic if farmers are to benefit from factor-biased changes in technology that save the land and labor that they supply.

U.S. farm output. Even if, as I suspect, the elasticity of demand for U.S. farm output is closer to –2.0 than –1.0, U.S. farmers *as a group* may have incurred losses as a result of their adoption of largely land- and labor-saving agricultural innovations.[12]

The estimated cost functions, presented earlier, may be informative in this context. As noted, estimates using the two datasets (from USDA and InSTePP) both indicate that technical change has been land-, labor-, and capital-saving, and "other inputs"-using.[13] In a counterfactual prediction from the estimated model using the InSTePP data for 1949–2007, to produce the actual quantity of output produced in 2007 in the absence of any technological changes (i.e., eliminating the time-trend effects) since 1949, the cost-minimizing quantities of land and labor would be 3.6 and 3.5 times the actual quantities; stated differently, technological changes since 1949 reduced the demand for land and labor by 73% and 71% (for capital, by 67% and for other inputs, by 37%) relative to the amounts that would have been demanded otherwise to produce that actual 2007 output quantity, thereby reducing average and total costs by 62%. In contrast, using the estimates based on the USDA data instead, technological changes reduced the demand for land and labor by 61% and 60%.

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[12] Matt Andersen and I estimated the elasticity of demand for U.S. aggregate farm output as –1.83 using the InSTePP indexes of prices and quantities for 1949–2002, in a price-dependent specification of demand (see Alston 2006, Appendix B). This estimate is similar to estimates we derived using a synthetic approach, based on underlying commodity-specific elasticities of supply and demand, and national shares of global production and consumption.

[13] Some types of innovations, such as higher-yielding varieties and fertilizers, can be seen as distinctly "land-saving" while some, such as mechanical harvesters and bulk handling machinery, are more clearly "labor-saving." Some others, however, such as the tractor, saved both human labor and animal power, and in doing so also saved much land used to grow feed for horses and mules (see, e.g., Olmstead and Rhode 2001).

This is only a partial answer to the question, since we have not taken into account the effect of less-costly production on increasing the total scale of production, and thus the demand for farmer-supplied inputs, when supply shifts down—here is where the output demand elasticity comes in. This output expansion effect may be sufficient to more-than offset the effects of input savings from neutral and biased changes in technology if demand is sufficiently elastic. However, demand would have to be significantly elastic ($\eta > 1.2$) for the estimated 62% reduction in the unit cost of production, to result in a large enough expansion in consumption and thus total factor demand to offset a 75% innovation-induced reduction in demand for land and labor, and leave farm incomes unaffected. Demand would have to be much more elastic for farmers to reap an appreciable share of the total national benefits.[14]

Evidence on changes in farm income—from the balance sheet of the farming sector—reinforces the idea that farming innovations have caused reductions in total income to farmers as a group. In its "Farm Income and Wealth Statistics" the USDA-ERS publishes annual estimates of "Net Farm Income," a measure that corresponds reasonably closely to the concept of income accruing to farmers, from farming, contemplated here.[15] Figure 2 shows the time path of U.S. Net Farm Income (NFI) in real (2009) dollars for the years 1929–2017. It also shows the Value of Agricultural Sector Production (VASP) and NFI as a percentage of VASP.

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[14] 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, in fact, will be made worse off if the adoption by others leads to output price reductions.

[15] This measure includes land rent accruing to farm operators who rent land to other farm operators, but does not include rent accruing to other landlords. For a subset of the time period for which the data were available I created an alternative measure: "Returns to Operators" plus "Net Returns to Landlords," which includes land rent accruing to both farm operators and others. This measure tracks Net Farm Income closely, but exceeds it by about 8% in recent years, with the difference representing mainly land rent accruing to others (i.e., not farm operators).

[Figure 2: U.S. Net Farm Income, 1929–2017]

In 1929, on the eve of the Great Depression, U.S. NFI was $62 billion. After plummeting to $27 billion in 1932, it fluctuated between $35 billion and $55 billion until the United States entered World War II, when it promptly doubled reflecting the wartime boom in demand for farm output. The 1940s saw NFI fluctuating in the range of $120 billion, with an historical peak in 1948 at almost $130 billion. During this 20-year period (1929–1948), land in farms continued to grow but average farm size grew even faster (see Alston et al. 2010, p. 17, Figure 2-5); meanwhile three-quarters of the remaining 20 million horses and mules were eliminated from farm production, and much human labor was also saved as farmers increasingly adopted tractors, combines, and other machines (see Alston et al. 2010, p. 29, Figure 3-1; Olmstead and Rhode 2001). The 1950s saw NFI declining rapidly to return in 1959 to the 1929 value of $62 billion. Since then, the trend in NFI has been fairly flat with notable fluctuations including the OPEC-induced commodities boom of the early 1970s followed by the bust of the early 1980s, and another oil-induced boom-bust sequence in the most recent decade.

Remarkably, the estimate of NFI for 2016 is $61 billion, slightly less than the 1929 value of $62 billion, and it will be less again in 2017 even though during those nine decades, total demand for U.S. farm output grew considerably, reflecting an increase in total U.S. population from 122 million to over 320 million combined with an increase in per capita income from $8,669 to $51,516 (in real 2009 dollars), augmented by a significant new demand for biofuels (Johnson and Williamson 2017). Indeed the value of sectoral output grew from $140 billion in 1929 to $363 billion in 2016 (in real 2009 dollars), but NFI as a share of VASP shrank from 50% in the 1940s to around 20% in recent years (see Figure 2).

It seems inescapable that the agricultural innovations that made food much more abundant and cheaper for consumers did so to some extent at the expense of farmers as a whole—more than offsetting the effects of growth in demand for output from the sector. This finding is reinforced when we pay attention to the details of the timing. Specifically, the periods of the most rapid decline (or slowest growth) in NFI seem to coincide with the periods of most rapid increase in farm productivity—the 1940s–1980s, especially 1950–1980, as identified by Alston, Andersen and Pardey (2017)—consistent with the hypothesis that agricultural innovations have reduced net incomes for U.S. farmers as a group. This finding refers to *functional* income distribution, at the level of the sector, rather than *personal* income distribution. Certainly, for those that remain in farming, average income per farmer is much greater today than it was 80 or even 40 years ago, but they are many fewer and the effect of the reduction in numbers of farmers outweighs the effect of the increase in income per farmer, such that total payments for land, labor and other inputs supplied by farmers has shrunk (see Appendix Table A-1). This is relevant to the question, looking forward: "would today's farmers *as a group* expect to benefit from investments in agricultural R&D?"

This discussion of benefits accruing to U.S. farmers as a group has abstracted from important elements of the question of who benefits from agricultural R&D, which can be considered in terms of the definition of the relevant counterfactual. Crucially when we hold the demand facing U.S. farmers constant in our analysis, we are implicitly assuming that producers in other countries are not able to adopt the technology in question. Consequently, producers in the rest-of-the-world (ROW) must lose when U.S. producers, facing a downward-sloping demand, adopt cost-reducing innovations and drive down the world price. Globally, the demand for farm products is highly inelastic, even when it is elastic for producers in any particular country. As illustrated in Figure 3, when a subset of the world's producers adopt a cost-saving innovation, some (and potentially more than all) of their benefits are necessarily at the expense of ROW producers (see, e.g., Edwards and Freebairn 1982, 1984): agricultural innovation led by the United States could conceivably have an immiserizing effect on farmers, globally, even if it benefits American farmers. Likewise, an agricultural treadmill, as first described by Cochrane (1958) and revisited by Levins and Cochrane (1996), might be evident as a global market phenomenon even if agricultural innovation yields net benefits to farmers taking a narrow national perspective. The same thinking applies if the producers not adopting the innovation in question are producers of other products that are substitutes in consumption: benefits from innovation come to some extent at the expense of farmers who are slow to adopt or never adopt the innovation.

[Figure 3: Distribution of Benefits: U.S. versus ROW Farmers]

5. U.S. Agricultural Productivity Slowdown

As discussed by Alston et al. (2010, p. 390, Box 11-1) in models of the links between agricultural (or industrial) research spending and productivity it is typically assumed that multifactor productivity (MFP_t in year t) depends on the current *stock* of useful knowledge (K_t in year t). This knowledge stock is based on a distributed lag (weighted sum) of L_R annual *flows* of investments in agricultural R&D (R_t in year t) that encompasses lags in the creation of knowledge and technology as well as in the technology adoption-cum-disadoption process. Assuming (as is typical) a model that is linear in logarithms, and incorporating other shift variables (V_t in year t):

(2) $\ln MFP_t = \beta_0 + \beta_1 \ln K_t + \beta_2 V_t + \varepsilon_t$, where $K_t = \sum_{r=0}^{L_R} w_r R_{t-r}, \text{and} \sum_{r=0}^{L_R} w_r = 1$.

Importantly, this conventional (and widely used) model imposes a finite lag distribution—the overall maximum lag is L_R years between making an investment in research, R_t, and its effects on productivity having been *entirely* exhausted—which has implications for the relationship between R&D investments and productivity. In this model, in a steady state, where research spending has been constant at R_{SS} for L_R years or more, the knowledge stock will be constant ($K_{SS} = R_{SS}, \text{and } d\ln K_{SS} = 0$)—effectively, all research spending is entirely "maintenance" research just sufficient to offset knowledge depreciation—and the growth rate of productivity will be zero: $d\ln MFP_{SS} = \beta_1 d\ln K_{SS} = 0$. In other words, growth in productivity requires growth in the knowledge stock which in turn requires growth in spending.

This proposition may seem surprising at first, but it is a clear implication of the extant work on the links between agricultural R&D and productivity.[16] Moreover, it does not require a great extrapolation outside the range of experience to envision and project a scenario of very slow, zero, or even negative growth in agricultural productivity. For example, using their preferred econometric model estimated using data for 1949–2002, Alston et al. (2010, pp. 385–390) projected MFP growth under two scenarios. In the "optimistic scenario" R&D spending in each state and federally would grow after 2002 at the respective average rate for the period 1949–2002; in the "pessimistic scenario" R&D spending would grow after 2002 at the average

[16] Recent econometric studies have typically allowed for a total lag length of 35 years or up to 50 years. The trapezoidal lag model from Huffman and Evenson (1989) has an overall lag of up to 35 years (in which most of the effect is exhausted by year 30) and the gamma lag distribution model from Alston et al. (2010, 2011) has an overall lag length of up to 50 years (in which most of the effect is exhausted after 40 years).

rate for the period 1990–2002. In the pessimistic projection, MFP grows slowly and at a diminishing rate (averaging 0.52 % per year 2003–2050), perpetuating the productivity slowdown the authors identified as beginning in the 1990s.

In fact, public spending on agricultural and food R&D since 2002 has grown even more slowly than allowed for in that pessimistic projection. According to Pardey et al. (2016), between 2000 and 2011 inflation-adjusted spending on public agricultural and food R&D increased only slightly (from 4.34 to 4.40 billions of 2009 PPP dollars, 1.4% in total over 11 years, or 0.12% per year). This trend reflects a *decline* in real public spending since 2009, which has continued in the years since, and the productivity implications may be more serious given the drift in emphasis away from farm productivity-oriented R&D within the total portfolio. (Private spending on agricultural and food R&D has grown more rapidly, but a large share is devoted to food R&D, and it is proprietary, with different implications for cost savings on farms compared with public R&D.)

The trends in public agricultural R&D spending would give us cause to anticipate and look for evidence of a slowdown in farm productivity growth. But the long lags and other complexities of the stock-flow relationships between investments in R&D and effects on productivity, combined with the complicated history of spending patterns, make it difficult to pin down the likely timing of a slowdown in MFP attributable to a slowdown in agricultural R&D spending. In an initial foray on this issue, using data for 1949–2002 we reported evidence of a productivity slowdown since 1990 (Alston et al. 2010); more recently, using data for 1910–2007, we have developed more comprehensive evidence indicative of a slowdown in U.S. farm productivity beginning much earlier, after a surge in MFP growth that peaked in the middle

1960s (Andersen et al. 2017; Alston et al. 2017).[17] The findings were consistent across procedures and measures of productivity, most transparently in tests for constant growth rates using cubic polynomial logarithmic trend models.

In Figure 4, the path of ln*MFP* is clearly (visibly) non-linear. A cubic polynomial trend model fits the data very closely ($R^2 = 0.994$) and the null hypothesis of a linear model with a constant growth rate is strongly rejected. The estimated parameters imply that the rate of MFP growth accelerated over the years prior to 1963 and slowed after 1963. These estimates support the view that U.S. farm productivity growth has slowed in recent decades. But more than that, they also suggest that this slowdown came after a period of unusually rapid productivity growth in the middle of the full sample period, 1910–2007, with slower rates both in the earlier decades (i.e., 1910–1930) and more recently (1990–2007).

[Figure 4: *Cubic Trend Model of MFP in Natural Logarithms, 1910–2007*]

To check whether their results were specific to the InSTePP data, Andersen at al. (2017) also estimated cubic trend regression models using data on U.S. agricultural TFP from USDA-ERS (2013), and state-level data. Using either the national or state-level data from either USDA or InSTePP the same qualitative conclusion is reached. Specifically, the null hypothesis of a linear model with constant growth is rejected in every instance in favor of a cubic model that implies a mid-century surge in farm productivity growth, followed by a slowdown as we approach and enter the 21st century. The slowdown is statistically significant but, compared with the InSTePP

[17] These findings regarding the existence, timing, and extent of a slowdown in U.S. farm productivity growth have been contested, mainly by economists working at the USDA-ERS. See, e.g., Ball, Wang and Nehring (2010); Wang (2010); Ball, Schimmelpfennig and Wang (2013); Wang et al. (2015a, 2015b); Fuglie et al. (2017).

data, the USDA data indicate a more recent inflection point. All of the models support a view that U.S. farm productivity growth has been slower since the 1980s than in the prior decades, as does other evidence.

Alston, Andersen and Pardey (2017) speculated that the slowdown in U.S. farm productivity growth might be attributable to a prior slowdown in spending on agricultural R&D. The models estimated by Alston et al. (2010, 2011) accounted for the postwar (1949–2002) path of MFP—including some elements of the slowdown described here—using measures of knowledge stocks that reflected the past time path of R&D spending (1890–2002). However, the timing of the slowdown revealed by the longer-term data (1910–2007), beginning in the 1960s, appears to be too early for it to be mainly attributable to a slowdown in the growth rate of a knowledge stock that includes 50 years of lagged R&D expenditure.

Alternatively, Alston, Andersen and Pardey (2017) conjectured that a wave of technological progress through the middle of the 20th century—reflecting the progressive adoption of various mechanical innovations, improved crop varieties and animal breeds, synthetic fertilizers and other chemicals, each in a decades long process—contributed to an extended surge of faster-than-normal productivity growth throughout the third quarter of the century, and a subsequent slowdown that has extended into the present era. They further speculated that a one-time surge in productivity, like this, could be an inherent feature of the economics of the agricultural transition, the essential feature of which is to shift the majority of the farmers and their families out of agriculture—a one-time change. International evidence might shed some light on this question.

6. International Agricultural Productivity Patterns

Most countries do not have agricultural statistics nearly as good as those for the United States prepared by USDA-ERS and InSTePP. Various studies of agricultural productivity patterns around the world have relied instead on FAOSTAT data, which are readily available for many countries and many years (FAOSAT, 2017). Using these resources primarily, Keith Fuglie has compiled measures of inputs, outputs and TFP for countries, regions and the world as a whole, in a useful form (see USDA-ERS, 2016). Studies using these or similar data have generally rejected the productivity slowdown hypothesis, and more often have reported an acceleration of productivity—especially but not exclusively in developing countries.[18]

Whether this is right matters for understanding the prospects for the world food equation and other important determinants of well-being around the world. In what follows I first use these data to explore the evidence from the cross-section related to the conjecture that agricultural productivity growth surges during the transition from an agrarian to an industrial economy. Next, I revisit the evidence from these versus other data on the U.S. productivity slowdown and draw inferences for what we can say with confidence about international agricultural productivity patterns.

The question of whether the agricultural transition entails a surge in agricultural productivity is large and serious, and difficult, and at this stage I can only offer sketchy evidence from preliminary analysis. Three alternative measures of national agricultural productivity

[18] See, for example, Fuglie (2008, 2010a, 2010b, 2012, 2015), various chapters in the volume edited by Fuglie, Wang and Ball (2012), the award-winning article by Trinidade and Fulginiti (2015), and OECD (2016).

growth (*G*)—including TFP and partial factor productivities for land and labor—were each regressed against a measure of the stage of economic development (*I* = GDP/capita in constant, 2005, international dollars), using annual data for a panel of 147 countries (or regional aggregates) over the years 1961–2014. The models, which include fixed effects for year, *t* and country, *i*, are quadratic forms in the logarithms of *I*, as follows:

$$(3)\ \ G_{i,t} = \alpha_0 + \alpha_1 \ln I_{i,t} + \alpha_2 \ln^2 I_{i,t} + \mu_{i,t}\ .$$

In Table 2, the regression results are similar when the models are applied to 10-year averages of productivity growth rates by decades, or to the (fairly volatile) annual measures, and they are comparable (though different in a way that can be rationalized) across the alternative productivity measures. In every case, the estimated models do not account for very much of the total variation in productivity growth rates, but the estimated coefficients on the linear and quadratic income terms are statistically significantly different from zero. The maximum predicted growth rate of TFP is reached when per capita GDP is $1,879 (column 1 in Table 2) or $1,858 (column 2).[19] Other evidence suggests that the maximum growth rates are likely to occur at higher per capita income. For example, in 2005 PPP dollars, U.S. per capita GDP was $18,830 in 1966, the year of maximum MFP growth from Andersen et al. (2017); in 2014 GDP per capita in China was $10,890, but it was close to $1,800 in 1993.

[Table 2: Models of a surge in international agricultural productivity, 1961–2013]

[19] The maximum predicted land productivity growth rate is reached later in the process when per capita GDP is $2,827 (column 3) or $3,726 (column 4); the maximum predicted labor productivity growth rate is reached when per capita GDP is $3,746 (in columns 5) or $3,292 (in column 6).

These preliminary results using the international data, are broadly consistent with the results from Andersen et al. (2017) using the U.S. state and national data, somewhat supportive of the idea that the U.S. productivity slowdown may be reflective of a more general phenomenon associated with the agricultural transition and not simply an idiosyncratic result reflecting the path of U.S. agricultural R&D spending—though both processes could be in play. This question is the subject of continuing work from which we hope to derive more definitive results. One cause for reservations is concern over the quality of the international TFP measures. As noted at the outset, "productivity" is always an unexplained residual. Schultz and Griliches identified elements of that residual that could be reduced in various ways, and significant progress in that direction has been made by both the USDA-ERS and InSTePP in their state and national U.S. agricultural productivity data series. However, in spite of Keith Fuglie's heroic efforts to do as much as can be done with the fundamental data resources that are available, the USDA-ERS international TFP measures leave a great deal still in the residual—in particular for the world's poorest countries.[20]

This aspect of these and other productivity measures based on FAOSTAT data, is not always acknowledged, and even when it is acknowledged, the implications are not always appropriately highlighted by users of the data. A recent publication by the OECD (2016) illustrates this point. It presents a figure, based on the USDA international agricultural

[20] Alston, Babcock and Pardey (2010) discuss some of the data and measurement problems in reviewing a chapter by Fuglie (2010) in a book they commissioned and edited. They conclude: "Fuglie's estimates are the only available estimates of agricultural TFP growth for many countries of the world in the recent period. Even so, they should be used carefully, given the many constraints that data and measurement realities and choices place on generating accurate estimates, and especially in relation to the question of a slowdown in productivity given that we have little basis for assessing their accuracy for that purpose."

productivity data, showing annual agricultural TFP growth rates for selected OECD countries, 1961–2012 and 2003–2012. Immediately prior to that figure the text (OECD, 2016, p. 58) reports:

> U.S. agricultural productivity has experienced sustained high rates of growth for decades. Using estimates from the ERS International Agricultural Productivity accounts, Total Factor Productivity (TFP) growth in the United States averaged 2.1% per year over 2003–12 and 1.47% per year over the longer period, 1961–2012 (Figure 2.13).

In other words, by these measures, and as Figure 2.13 illustrates, U.S. agricultural TFP growth accelerated since 2003. In the next paragraph, however, the text acknowledges that the "…international TFP comparisons are hampered by data limitations. In particular, they only crudely account for certain important inputs like pesticides and contract services" (OECD, 2016, p. 58), and points towards the "more comprehensive" domestic productivity accounts produced by USDA-ERS. But the reader is not cautioned to ignore (or even discount) the apparent evidence of Figure 2.13 or the suggestion that farm productivity growth has accelerated in the United States even though the more reliable evidence from national accounts suggests otherwise.[21]

Table 3 compares measures of U.S. agricultural productivity growth from three sources: InSTePP, the USDA-ERS national accounts, and the USDA-ERS international accounts. In each case the entries are computed either by regressing the productivity index in logarithms against a linear time trend (denoted "OLS") or simply as the average of annual growth rates (denoted

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[21] The same Figure (OECD 2016) also suggests a significant productivity acceleration in Australia whereas various analyses of national data sources by economists at ABARES and elsewhere have reported a significant slowdown (see, e.g., Sheng, Mullen and Zhao, 2011).

“Mean”). In principle, these measures are meant to represent the same concept, and the magnitudes should be similar; in practice, the differences are striking. Consider, first, the last row of entries, representing average annual growth rates for the entire period (1961–2007) for which data are available from all three sources. Both measures based on the USDA “International” data (columns 5 and 6), are similar, at around 1.4% per year implying total growth over 46 years of just 90%. The two alternative sets of estimates based on national accounts both indicate much faster average annual growth rates: 1.6 or 1.8% from USDA-ERS “National” data (columns 3 and 4) and around 1.8% from InSTePP (columns 1 and 2), the latter implying total growth over 46 years of 127%, 1.40 times the total growth implied by the USDA “International” data. The patterns over time are also quite dissimilar. The USDA “International” data show a continuing acceleration in productivity growth from less than 1.2% before 1981 to 1.6% per year since 1981 and more than 1.7% per year since 1991. Both the USDA “National” accounts data and InSTePP show a slowdown since 1991, compared with the previous period, but in the case of InSTePP that slowdown was already evident after 1981, whereas in the USDA “National” accounts data, it became evident later, after an acceleration in the 1980s.

[Table 3. Annual average growth rates in U.S. agricultural productivity, 1961–2007]

The upshot of this comparison is first to confirm that the USDA “International” agricultural productivity data could be highly misleading as an indicator of U.S. agricultural productivity patterns, compared with either of the available alternatives that are based on a more complete accounting of the inputs, especially capital. In addition, although we do not have available alternative measures based on national accounts that we can use to check directly for most other countries, it seems reasonable to suppose that the measurement problems that bedevil the estimates for the United States would be at least as bad for other countries for which the FAOSTAT measures of inputs and outputs would be subject to even greater deficiencies.[22]

A part of the problem is that these measures based on the FAOSTAT data have gone only a short way down the path required to fully account for (and eliminate) the productivity residual—as proposed by Schultz and Griliches. Another part is that the underlying FAOSTAT data on inputs and outputs may contain substantial measurement errors, especially for poorer countries. The measurement errors in the USDA "International" agricultural productivity data might be particularly troublesome in relation to measuring the shape of the time path of productivity growth, but the discrepancy in the estimates of overall productivity growth 1961–2007 is also troublesome. These comparisons certainly cast into doubt the findings from studies that have sought to test for a slowdown in agricultural productivity growth rates using these or similar measures based on FAOSTAT data—including those presented in Table 2 of this paper![23]

7. Conclusion

I began with a tribute to Schultz and Griliches who launched the economics of agricultural R&D and productivity around the time of my third birthday. Since then, much has been accomplished by economists working on this subject, but I opted here to focus less on

[22] Josef Schmidhuber has advised me that he and colleagues are engaged in developing an alternative set of measures of national agricultural productivity growth rates, based on national accounts.

[23] Leontief (1971, p. 3) justly complained: "…in all too many instances, sophisticated statistical analysis is performed on a set of data whose exact meaning and validity are unknown to the author, or rather so well known to him that, at the very end he warns the reader not to take the material conclusions of the entire 'exercise' seriously."

those accomplishments and more on the unfinished business and some unsettled questions about agricultural productivity, how it is measured, what it's worth, who benefits, and so on. As well as being somewhat negative by nature, this chosen path entailed a risk of being seen as negatively critical of others, which was not my purpose and is something I hope I have been able to avoid.

The first main point is that agricultural productivity matters, and it probably does not get enough of the right kinds of attention. If we want to understand the economics of agricultural production, the main action is in the productivity "residual." In the United States, over the past half-century and more, the "unconventional" inputs (of land, other natural resources, labor, capital, and materials) that went into "productivity" account for more than 100% of the very substantial growth in agricultural production, saving enormous quantities of "conventional" inputs (of land, other natural resources, labor, capital, and materials) that otherwise would have been demanded by a much less-productive agriculture. Indeed, "unconventional" inputs in the form of organized agricultural R&D have much more than paid their way, yet the United States (like other nations) persists in doing too little. We have done a comprehensive job as a profession of documenting the high social payoff to agricultural R&D investments, which implies a very significant government failure in the provision of agricultural R&D. But we have not done nearly so well as a profession at documenting the social cost of that government failure or at devising workable solutions that governments will find attractive to adopt.

The second main point relates to factology. We have available multiple sets of measures of aggregate agricultural inputs, outputs, and productivity, and we can afford to spend more of our time and other resources investing in improving these assets and understanding them better before we put them to use.[24] In the United States we are uncommonly rich in this regard: we have three national aggregate datasets that are in active use (InSTePP, USDA-ERS national accounts, and USDA-ERS international accounts), and for two of these we also have detailed state-level data (InSTePP and the USDA-ERS national). This comparative wealth of data resources allows us to revisit some points raised by Gardner (1992) that have a more general relevance beyond the specific context.

Results presented here confirm Gardner's suggestion that we should pay attention to the sources of our data and how they are created. In the context of a translog cost function model, for example, the choice of dataset (between InSTePP and the USDA-ERS national accounts) could imply materially different estimates of factor demand elasticities or the rate and factor bias of technological change. The choice of data set could also imply materially different views about the time path of productivity change in terms of the overall rate, whether it was accelerating or slowing, and when. Compared with both the USDA national accounts and InSTePP, the data from the USDA-ERS international accounts indicate much slower overall U.S. agricultural productivity growth since 1961. Further the USDA international accounts indicate a huge acceleration whereas both the USDA "National" accounts data and InSTePP show a slowdown since 1991. Work remains to be done to resolve the debate over how best to measure the price and quantity of capital—the most important source of difference between

[24] The socially productive work of creating and validating data resources is undervalued generally, if not derided. As Alice Rivlin (1975, p. 4) stated in her Ely lecture: "Disdain for data collection is built into the value and reward structure of our profession. Ingenious efforts to tease bits of evidence from unsuitable data are much applauded; designing instruments for collecting more appropriate information is generally considered hack work."

InSTePP the USDA-ERS national accounts. I am inclined to favor the InSTePP measures for the reasons presented by Andersen et al. (2011), buttressed by the cost function analysis presented here. But clearly I cannot be entirely neutral on this question, having some personal professional investment in the InSTePP data. Other analysis here raises some serious concerns over the interpretation and use of productivity measures in the USDA-ERS international accounts, which is especially bothersome because no comparable alternative exists for many countries or for making international comparisons. Even when we have grave concerns about the data, the temptation to use them nevertheless to conduct analysis can be overwhelming. At a minimum, I would prescribe a very large grain of salt and much caution as we wait and hope for improved estimates to become available.

In much of my own work I have argued that farmers should expect to benefit from agricultural R&D, but it has been troubling not to have direct, compelling empirical evidence to support this view (e.g., Alston et al. 2009). Here, I have tried seriously to answer that question for the first time, and the answer came as a surprise. First, a fairly simple but transparent theoretical analysis suggests that when demand for the farm product is inelastic, farmers as a group can expect to lose from factor neutral technical change or from factor-biased technical change that saves inputs supplied by farmers. Second, both the cost function estimates and informal evidence (technology factoids) indicate that technological change in U.S. agriculture has been land- and labor-saving; and, even though the demand for U.S. farm output is probably elastic, it might not be elastic enough to offset these farmer-supplied-input-saving effects. Third, U.S. net farm income (NFI) has shrunk as a share of gross farm income to an extent such that, in real terms, total NFI has been roughly constant since 1960. NFI today is close to the value in 1929 even though in the nine decades since, U.S. population and per capita income and demand for farm output have increased manifold.

Drawing these elements together, it seems inescapable that American farmers *as a group* have been made worse off by the changes in technology that transformed America agriculture—which in no way implies that American farmers can afford to cease to innovate! The comparison here is with a counterfactual scenario in which (implicitly) agricultural technology could have been frozen not only in the United States but also everywhere else. It would be even worse for American farmers if they were to cease unilaterally to innovate while farmers in the rest of the world did not. A related question concerns distribution among farmers. Even if U.S. farmers do stand to benefit from technological changes of the types experienced since WWII, given that worldwide demand for farm output is inelastic, it follows that farmers somewhere will have been made worse off. The question "do farmers benefit from agricultural R&D?" has to be asked carefully (with attention to which famers and under what corollary conditions) if we want meaningful answers. Farmers and farm lobby groups appear to be much more interested in seeking government support for subsidized crop insurance and the like rather than agricultural R&D; and perhaps they are well-advised in so doing. A better understanding of the ultimate incidence of research benefits might help us do better at finding solutions to the problem of underfunding of agricultural R&D.

8. References

Acquaye, Albert K.A., Julian M. Alston and Philip G. Pardey. "Post-War Productivity Patterns in U.S. Agriculture: Influences of Aggregation Procedures in a State-Level Analysis." *American Journal of Agricultural Economics* 85(1)(February 2003): 59–80.

Alston, Julian M. "Benefits and Beneficiaries from U.S. Farm Subsidies." Paper 4 of *Agricultural Policy for 2007 Farm Bill and Beyond*, Bruce L. Gardner and Daniel A. Sumner, editors, presented at the AEI conference, Washington DC, December 5-6, 2006. (available at http://aic.ucdavis.edu/research/farmbill07/aeibriefs/20070515_alstonSubsidiesfinal.pdf)

Alston, Julian M. "Efficiency of Income Transfers to Farmers through Public Agricultural Research—Theory and Evidence from the United States." *American Journal of Agricultural Economics* 91(5) (December 2009): 1281–1288.

Alston, Julian M., Matthew A. Andersen, Jennifer S. James, and Philip G. Pardey. *Persistence Pays: U.S. Agricultural Productivity Growth and the Benefits from Public R&D Spending*. New York, NY: Springer, 2010a.

Alston, Julian M., Matthew A. Andersen, and Philip G. Pardey. "The Rise and Fall of American Farm Productivity Growth." St. Paul: International Science and Technology Practice and Policy (InSTePP) Center, University of Minnesota Staff Paper P15-02, January 2015. Available at http://ageconsearch.umn.edu/record/200927?ln=en (revised, 2017)

Alston, Julian M., Bruce A. Babcock and Philip G. Pardey. "Shifting Patterns of Global Agricultural Productivity: Synthesis and Conclusion." Chapter 15 in J.M. Alston, B.A. Babcock and P.G. Pardey eds *The Shifting Patterns of Agricultural Production and Productivity Worldwide*, CARD-MATRIC on-line volume, Ames, IA: Center for Agricultural and Rural Development, 2010b. Available at http://lib.dr.iastate.edu/card_books/2/

Alston, Julian M. and Philip G. Pardey. "Agriculture in the Global Economy" *Journal of Economic Perspectives* 28(1)(2014): 121–146.

Alston, Julian M. and Philip G. Pardey. "Transforming Traditional Agriculture Redux." Chapter in Célestin Monga and Justin Yifu Lin, eds, *(Oxford) Handbook of Structural Transformation*. Oxford: Oxford University Press (in process, 2017) (also published as World Bank Working Paper series No 260, 2017, available at https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/WPS_No_260_Transforming_Traditional_Agriculture_Redux_Z.PDF)

Alston, Julian M., Philip G. Pardey, Jennifer S. James, and Matthew A. Andersen. "A Review of Research on the Economics of Agricultural R&D." *Annual Reviews of Resource Economics* 1(October 2009): 537–565.

Andersen, Matthew A., Julian M. Alston and Philip G. Pardey. "Capital Services in U.S. Agriculture: Concepts, Comparisons, and the Treatment of Interest Rates." *American Journal of Agricultural Economics* 93(3)(2011): 714-34.

Andersen, Matthew A., Julian M. Alston and Philip G. Pardey. "Erratum—Capital Services in U.S. Agriculture: Concepts, Comparisons, and the Treatment of Interest Rates: An Error and a Correction." *American Journal of Agricultural Economics* 94(5)(2012): 1247–1248.

Andersen, Matthew A., Julian M. Alston and Philip G. Pardey. "A Secular Slowdown of U.S. Farm Productivity Growth?" Draft manuscript, April 2017.

Ball, Eldon, David Schimmelpfenning and Sun Ling Wang. "Is U.S. Agricultural Productivity Growth Slowing?" *Applied Economic Perspectives and Policy* 35 (3) (2013): 435–50.

Ball, Eldon, Sun Ling Wang, and Richard Nehring. Agricultural Productivity in the United States: Data Documentation and Methods. Washington D.C.: USDA Economic Research Service, May 2010. Accessed July 2010, from www.ers.usda.gov/data/agproductivity/methods.htm.

Ball, Eldon, Sun Ling Wang, Richard Nehring, and Roberto Mosheim. "Productivity and Economic Growth in U.S. Agriculture: A New Look" *Applied Economic Perspectives and Policy* 38 no. 1 (2016): 30–49.

Clancy, Matthew, Keith O. Puglie and Paul Heisey. "U.S. Agricultural R&D in an Era of Falling Public Funding." *Amber Waves* USDA-ERS, November 10, 2016. Available at https://www.ers.usda.gov/amber-waves/2016/november/us-agricultural-rd-in-an-era-of-falling-public-funding/

Cochrane, Willard W. *Farm Prices: Myth and Reality.* Minneapolis: University of Minnesota Press, 1958.

Cochrane, Willard W. *The Development of American Agriculture: A Historical Analysis*. Second Edition, Minneapolis: University of Minnesota Press, 1993.

Craig, B.J. and P.G. Pardey. "Productivity Measurement in the Presence of Quality Change." *American Journal of Agricultural Economics* 78(5)(December 1996): 1349-1354.

Edwards, Geoff W. and John W. Freebairn. "The Social Benefits from an Increase in Productivity in Part of an Industry." *Review of Marketing and Agricultural Economics* 50(1982): 193–210.

Edwards, Geoff W. and John W. Freebairn. "The Gains from Research Into Tradable Commodities." *American Journal of Agricultural Economics* 66(1)(February 1984): 41–49.

FAOSTAT. A Database of the Food and Agriculture Organization of the United Nations (FAO). Retrieved July 2017 from http://faostat.fao.org.

Fuglie, Keith O. "Is a Slowdown in Agricultural Productivity Growth Contributing to the Rise in Agricultural Prices?" *Agricultural Economics* 39(2008): 431–44.

Fuglie, Keith O. "Total Factor Productivity in the Global Agricultural Economy: Evidence from FAO Data." Chapter 4 in J.M. Alston, B.A. Babcock and P.G. Pardey eds *The Shifting Patterns of Agricultural Production and Productivity Worldwide*, CARD-MATRIC on-line volume, Ames, IA: Center for Agricultural and Rural Development, 2010a. Available at http://www.card.iastate.edu/products/books/shifting_patterns/pdfs/chapter4.pdf.

Fuglie, Keith O. “Accelerated Productivity Growth Offsets Decline in Resource Expansion in Global Agriculture.” *Amber Waves* 8, no.3 (2010b): 46–51. Available at www.ers.usda.gov/Amberwaves/.

Fuglie, Keith O. “Productivity Growth and Technology Capital in Global Agriculture.” Chapter 16 in K.O. Fuglie, S.L. Wang, and V.E. Ball, eds. *Productivity Growth in Agriculture: An International Perspective.* Wallingford: CAB International, 2012.

Fuglie, Keith O. “Accounting for Growth in Global Agriculture.” *Bio-based and Applied Economics* 4, no.3 (2015): 201–234.

Fuglie, Keith O., Matthew Clancy, Paul Heisey, and James MacDonald “Research, Productivity, and Output Growth in U.S. Agriculture.” *Journal of Agricultural and Applied Economics* (2017), published online, 19 July 2017, DOI: https://doi.org/10.1017/aae.2017.13

Fuglie, Keith O. and A.A. Toole. “The Evolving Institutional Structure of Public and Private Agricultural Research.” *American Journal of Agricultural Economics* 96(3)(2014): 862–883.

Fuglie, Keith O., Sun Ling Wang, and V. Eldon Ball, eds. *Productivity Growth in Agriculture: An International Perspective.* Wallingford: CAB International, 2012.

Gardner, Bruce L., D. Durost, William Lin, Y-C. Lu, G. Nelson, and N. Whittlesey. *Measurement of U.S. Agricultural Productivity: A Review of Current Statistics and Proposals for Change.* Washington DC: USDA, Economics, Statistics, and Cooperatives Service, Technical Bulletin No. 1614, 1980.

Gardner, Bruce L. “How the Data We Make Can Unmake Us: Annals of Factology.” *American Journal of Agricultural Economics* 74(5)(1992): 1066–75.

Gardner, Bruce L. *American Agriculture in the Twentieth Century: How It Flourished and What It Cost.* Cambridge: Harvard University Press, 2002.

Griliches, Zvi. “The Sources of Measured Productivity Growth: Agriculture, 1940–1960.” *Journal of Political Economy* 71(4)(1963): 331–346.

Griliches, Zvi. “Productivity, R&D, and the Data Constraint.” *American Economic Review* 84(1)(March 1994): 1-23.

Griliches, Zvi. “R&D and Productivity: The Unfinished Business” Chapter in Z. Griliches *R&D and Productivity: The Econometric Evidence*. Chicago: Chicago University Press, 1996.

Huffman, W.E., and R.E. Evenson. “Supply and Demand Functions for Multiproduct U.S. Cash Grain Farms: Biases Caused by Research and other Policies.” *American Journal of Agricultural Economics* 71(August 1989):761-773.

Johnston, Louis, and Samuel H. Williamson. “What Was the U.S. GDP Then?” *MeasuringWorth*, 2017. Available at http://www.measuringworth.org/usgdp/ (accessed July 17, 2017)

Mayer, Thomas. *Truth versus Precision in Economics*. Aldershot: Edward Elgar Publishing Company, 1993.

Levins, Richard A., and Willard W. Cochrane *Land Economics* 72(4) (1996): 550–553.

Leontief, Wassily. “Theoretical Assumptions and Nonobservable Facts.” *American Economic Review* 61(March 1971): 1–7.

OECD. *Innovation, Agricultural Productivity and Sustainability in the United States.* OECD Food and Agricultural Reviews, OECD Publishing, Paris, 2016. Available at http://dx.doi.org/10.1787/9789264264120-en

Olmstead, Alan L. and Paul W. Rhode. “Reshaping the Landscape: The Impact and Diffusion of the Tractor in American Agriculture, 1910-1960.” *The Journal of Economic History* 61, no.3 (2001): 663–98.

Olmstead, Alan L. and Paul W. Rhode. *Creating Abundance: Biological Innovation and American Agricultural Development*. New York: Cambridge University Press, 2008.

Pardey, P.G., J.M. Alston and C. Chan-Kang. 2013. *Public Food and Agricultural Research in the United States: The Rise and Decline of Public Investments, and Policies for Renewal*. Washington, DC: AGree Policy Report. Available at http://www.foodandagpolicy.org/sites/default/files/AGree-Public%20Food%20and%20Ag%20Research%20in%20US-Apr%202013.pdf

Pardey, Philip G., Matthew A. Andersen, Barbara J. Craig, and Julian M. Alston. Primary Data Documentation U.S. Agricultural Input, Output, and Productivity Series, 1949–2002 (Version 4). InSTePP Data Documentation. St Paul, MN: International Science and Technology Practice and Policy Center, University of Minnesota, 2009.

Pardey, Philip G. and Jason M. Beddow. “Revitalizing Agricultural Research and Development to Sustain US Competitiveness.” Commissioned Paper, Farm Journal Foundation, 2017. Available at http://www.farmersfeedingtheworld.org/assets/7/6/revitalizingagresearch_print.pdf

Pardey, P.G. and B. Craig. “Causal Relationships Between Public Sector Agricultural Research Expenditures and Output.” *American Journal of Agricultural Economics* 71(February 1989): 9–19.

Rao, Xudong, Terrance M. Hurley, and Philip G. Pardey. “Are Agricultural R&D Returns Declining and Development Dependent?” Selected Paper presented at the annual meeting of the Agricultural & Applied Economics Association, Boston, MA, July 31–August 2, 2016. Available at http://ageconsearch.umn.edu/record/235962.

Rivlin, Alice. “Income Distribution–Can Economists Help?” *American Economic Review* 65(May 1975): 1–15.

Shumway, C. Richard, Barbara M. Fraumeni, Lilyan E. Fulginiti, Jon D. Samuels, and Spiro E. Stefanou. “Measurement of Agricultural Productivity: A 2014 Review of Current Statistics and Proposals for Change.” Report of the Agricultural Productivity Review Committee to the USDA Economic Research Service. Reproduced as School of Economic Sciences Working Paper 2015–12, Washington State University, 2015. Available at: http://ses.wsu.edu/wp-content/uploads/2015/06/WP2015-12.pdf (accessed July 17, 2017).

Shumway, C. Richard, Barbara M. Fraumeni, Lilyan E. Fulginiti, Jon D. Samuels, and Spiro E. Stefanou. "U.S. Agricultural Productivity: A Review of USDA Economic Research Service Methods." *Applied Economic Perspectives and Policy* 38(1) (2016): 1–29.

Schultz, Theodore W. "Reflections on Agricultural Production, Output and Supply." *Journal of Farm Economics* 38(1956):748–762.

Sheng, Yu, John D. Mullen and Shiji Zhao. "A Turning Point in Productivity: Consideration of the Causes." ABARES Research Report 11.4 for the Grains Research and Research and Development Corporation, Canberra, May 2011.

Timmer, C. Peter. *A World without Agriculture: The Structural Transformation in Historical Perspective.* Washington, D.C.: American Enterprise Institute Press, 2009.

Trinidade, Federico, and Lilyan E. Fulginiti. "Is There a Slowdown in Agricultural Productivity Growth in South America?" *Agricultural Economics* 46 (2015, supplement): 69–81.

USDA-ERS (United States Department of Agriculture, Economic Research Service). "Table 1—Indices of Farm Output, Input and Total Factor Productivity for the United States, 1948-2011," Washington, D.C: USDA-ERS, September 27, 2013. Downloaded in June 2017 from https://www.ers.usda.gov/data-products/agricultural-productivity-in-the-us/.

USDA-ERS (United States Department of Agriculture, Economic Research Service). "Agricultural Total Factor Productivity Growth Indices for Individual Countries, 1961–2013," Washington, D.C: USDA-ERS, last updated October 7, 2016. Downloaded in June 2017 from https://www.ers.usda.gov/data-products/international-agricultural-productivity/

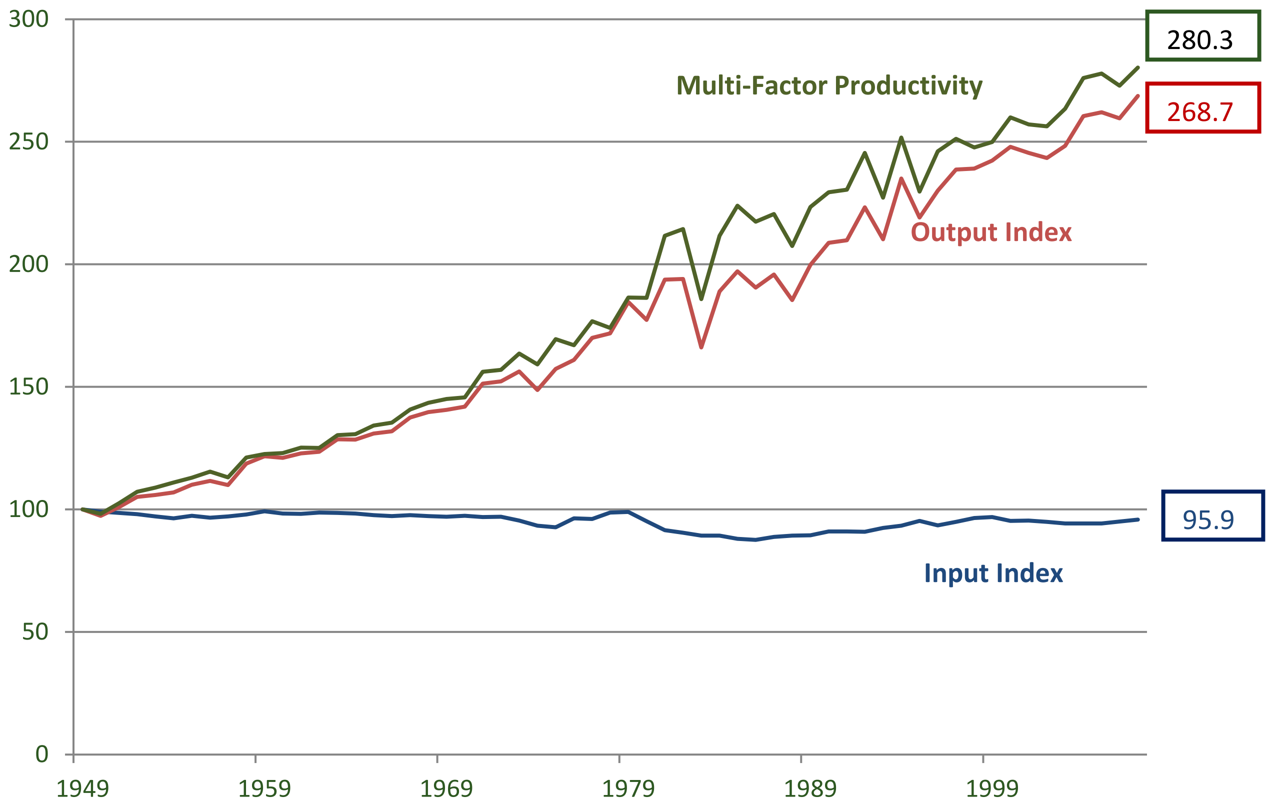
USDA-ERS (United States Department of Agriculture, Economic Research Service). "Value Added to the U.S. Economy by the Agricultural Sector, 1910–2017F, Real (2009 dollars)." Washington, D.C: USDA-ERS, 2017. Downloaded in June 2017 from https://www.ers.usda.gov/data-products/farm-income-and-wealth-statistics/data-files-us-and-state-level-farm-income-and-wealth-statistics/.

Wang, Sun Ling. "Is U.S. Agricultural Productivity Growth Slowing?" *Amber Waves* 8, no.3 (2010): 6. Available at www.ers.usda.gov/Amberwaves/.

Wang, Sun Ling, Paul Heisey, David Schimmelpfennig, and Eldon Ball. *Agricultural Productivity Growth in the United States: Measurement, Trends, and Drivers*, ERR-189, U.S. Department of Agriculture, Economic Research Service, July 2015a.

Wang, Sun Ling, Paul Heisey, David Schimmelpfennig, and Eldon Ball. "U.S. Agricultural Productivity Growth: The Past, Challenges, and the Future." *Amber Waves* Feature, September 2015b.

Figure 1: Inputs, outputs and MFP in U.S. agriculture, 1949–2007



Sources: Index numbers from Version 5 of the InSTePP Production Accounts.

Table 1: Results from translog cost function models applied to U.S. agriculture, 1949–2007

Panel a. Elasticities of factor demand and elasticities of substitution, at sample means

Hicksian Elasticities of Factor Demand			Elasticities of Substitution		
	USDA	InSTePP		USDA	InSTePP
η_{kk}	0.04	–0.19	σ_{kk}	0.30	–1.40
η_{kl}	0.03	–0.08	σ_{kl}	0.20	–0.49
η_{kh}	–0.04	0.10	σ_{kh}	–0.20	0.28
η_{ko}	–0.03	0.18	σ_{ko}	–0.06	0.54
η_{lk}	0.03	–0.07	σ_{lk}	0.20	–0.49
η_{ll}	–0.29	–0.31	σ_{ll}	–1.88	–1.80
η_{lh}	0.12	0.37	σ_{lh}	0.56	1.04
η_{lo}	0.15	0.01	σ_{lo}	0.30	0.02
η_{hk}	–0.03	0.04	σ_{hk}	–0.20	0.28
η_{hl}	0.09	0.18	σ_{hl}	0.56	1.04
η_{hh}	–0.40	–0.63	σ_{hh}	–1.89	–1.78
η_{ho}	0.34	0.42	σ_{ho}	0.69	1.25
η_{ok}	–0.01	0.07	σ_{ok}	–0.06	0.54
η_{ol}	0.05	0.00	σ_{ol}	0.30	0.02
η_{oh}	0.15	0.44	σ_{oh}	0.69	1.25
η_{oo}	–0.65	–0.73	σ_{oo}	–0.37	–1.56

Panel b. Annual rates of factor neutral and factor biased technical change

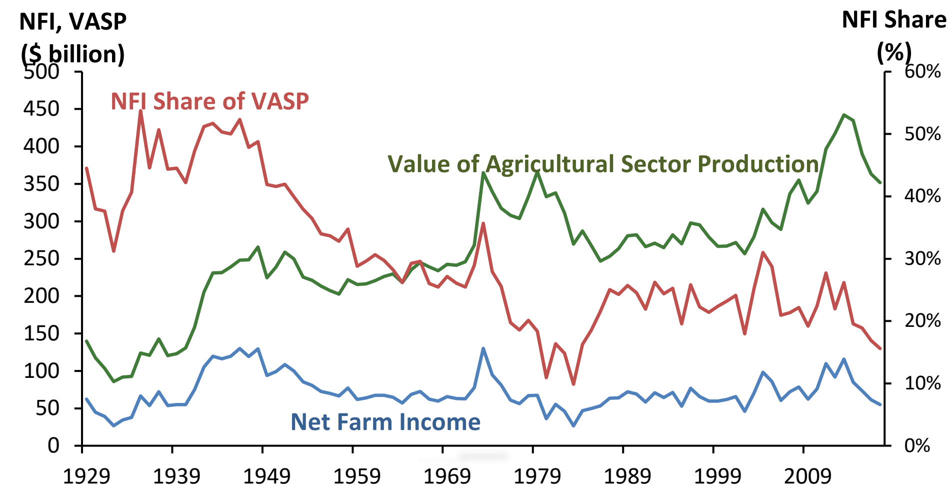
Input	USDA	InSTePP
Capital (k)	−0.0001	−0.0004
Land (l)	−0.0011	−0.0009
Labor (h)	−0.0023	−0.0016
Other (o)	0.0036	0.0029
Neutral	−0.0076	−0.0151

Source: Derived from estimates of cost functions, further details available from the author upon request.

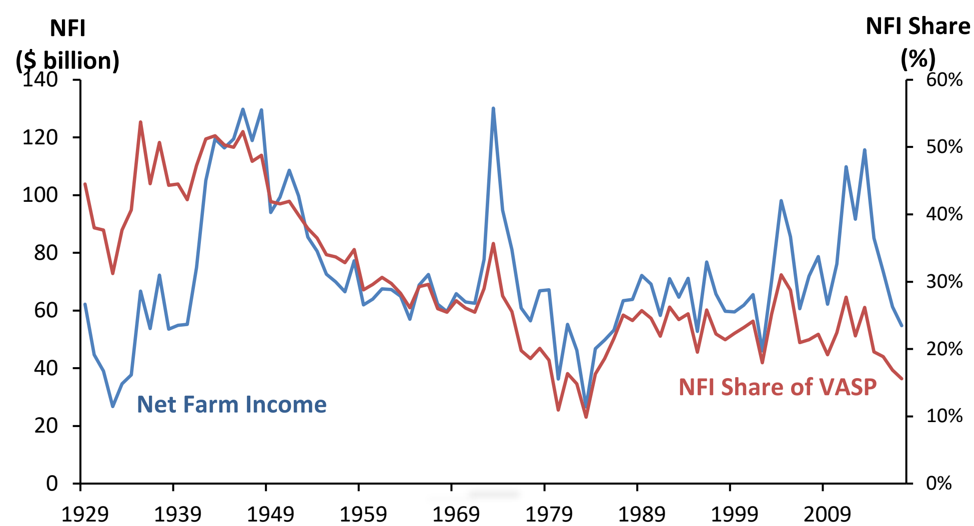
Notes: "USDA" and "InSTePP" denote sources of data used for estimating cost fuctiuon models using data for the period 1949–2007. The indexes are "k" for capital, "l" for land, "h" for "labor" and "o" for the aggregate of all other inputs. In Panel a, all of the coefficient estimates used in calculating the elasticities were statistically significantly different from zero at the 95% level of confidence, as were all the estimates in Panel b, except for the rate of capital–saving technical change estimated using the USDA data (highlighted). In Panel b, a negative coefficient indicates factor-saving technical change.

Figure 2: U.S. Net Farm Income, 1929–2017 (constant 2009 dollars)

Panel a. NFI, VASP, and NFI as a share of VASP



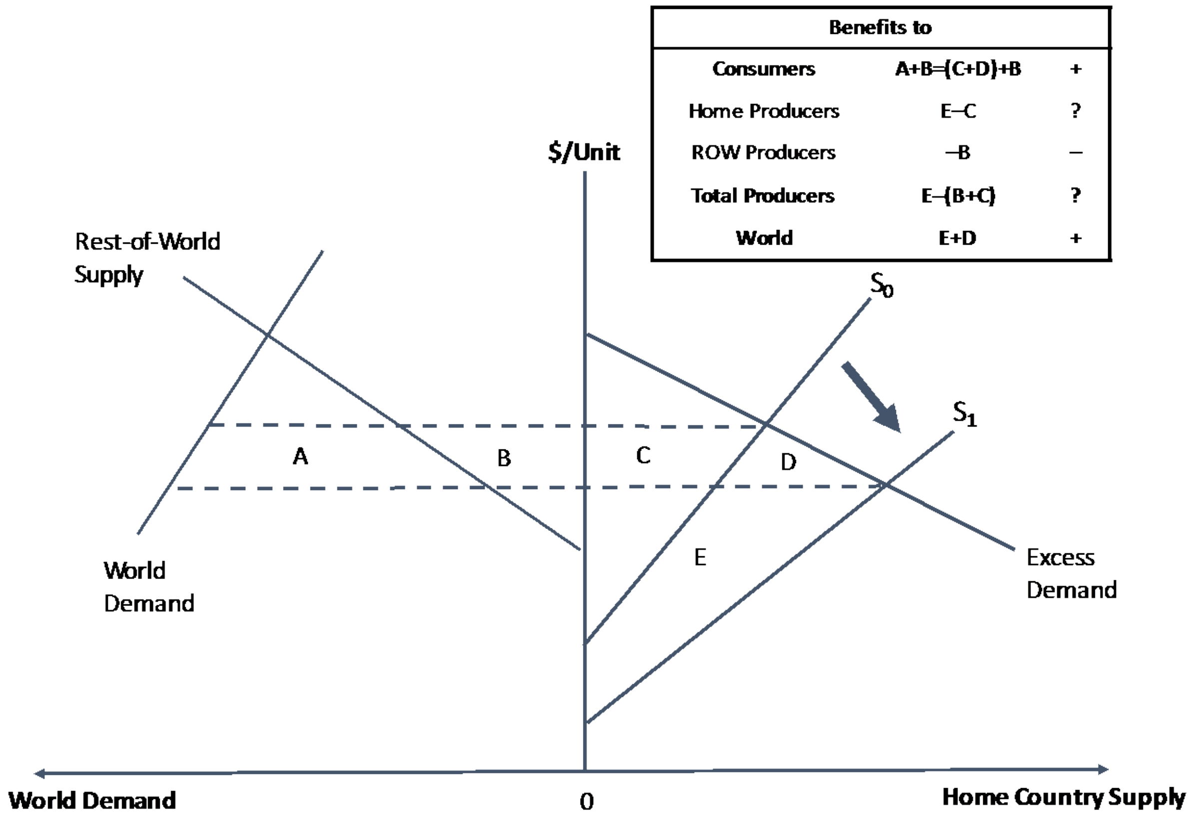
Panel b. NFI, and NFI as a share of VASP



Source: Created by the author using data from USDA-ERS (2017).

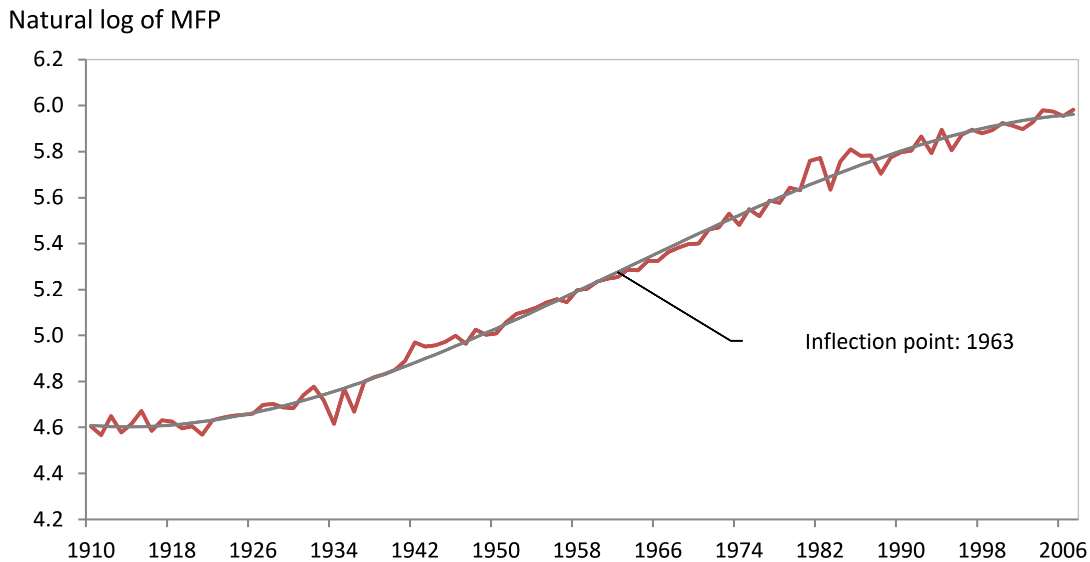
Notes: Nominal values were deflated using the GDP Implicit Price Deflator (base year 2009). NFI Ratio is Net Farm Income (NFI) as a percentage of the Value of Agricultural Sector Production (VASP).

Figure 3. Distribution of Benefits: U.S. versus ROW Farmers



Benefits to		
Consumers	**A+B=(C+D)+B**	**+**
Home Producers	E–C	?
ROW Producers	–B	–
Total Producers	**E–(B+C)**	**?**
World	**E+D**	**+**

Figure 4: *Cubic Trend Model of MFP in Natural Logarithms, 1910–2007*



Source: Andersen, Alston and Pardey (2017).

Table 2: Models of a surge in international agricultural productivity, 1961–2013

Variable	TFP Growth		Land PFP Growth		Labor PFP Growth	
	Annual	10-Year Average	Annual	10-Year Average	Annual	10-Year Average
	(1)	(2)	(3)	(4)	(5)	(6)
ln(*I*)	0.0340**	0.0354**	0.0627***	0.0809***	0.0627***	0.0585***
	(0.0157)	(0.0158)	(0.0210)	(0.0232)	(0.0141)	(0.0187)
$\ln^2(I)$	–0.00225**	–0.00235**	–0.00395***	–0.00492***	–0.00381***	–0.00361***
	(0.00100)	(0.00101)	(0.00134)	(0.00147)	(0.000853)	(0.00114)
Constant	–0.117*	–0.126**	–0.221***	–0.307***	–0.225***	–0.208***
	(0.0612)	(0.0620)	(0.0823)	(0.0913)	(0.0596)	(0.0770)
R^2	0.022	0.064	0.014	0.055	0.030	0.047
No. of Obs.	7,644	735	7,644	735	7,644	735
*I**	1,878.90**	1,857.56**	2,827.38***	3,726.39***	3,746.13***	3,292.15**
	(756.12)	(824.97)	(938.02)	(1,284.50)	(1,150.08)	(1,330.86)

Source: Estimated by the author using data from FAOSTAT and USDA (2016).

Notes: *I* and *I** are measured in 2005 PPP $/capita. The TFP data are available for 173 countries. Consistent data on GDP/capita were not readily available for 11 countries, which were dropped (these countries are not agriculturally significant: Brunei Darussalam, French Guiana (France), Korea, DPR, Kuwait, Lesser Antilles, Micronesia, New Caledonia (France), Polynesia, Réunion (France), Taiwan (China), and United Arab Emirates). Another 15 countries are included in the aggregate representing the Former Sovet Union: Estonia, Latvia, Lithuania, Armenia, Azerbaijan, Georgia, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, Belarus, Kazakhstan, Moldova, Russian Federation, Ukraine. We are left with a total of 147 individual countries or regions (147 = 173 – 11 – 15). *I** is the value of per capita income at which the predicted growth rate is maximized. It is computed as *I** = $\exp\{-\alpha_1/2\alpha_2\}$. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Table 3. Annual average growth rates in U.S. agricultural productivity, 1961–2007

Period	Productivity Indexes					
	In STePP, MFP		USDA-ERS, TFP (National Data)		USDA-ERS, TFP (International Data)	
	OLS	Mean	OLS	Mean	OLS	Mean
	(1)	(2)	(3)	(4)	(5)	(6)
1961–1971	2.06	2.20	1.52	1.74	0.67	0.74
1971–1981	2.56	3.04	0.98	1.41	1.49	1.61
1981–1991	1.08	0.86	2.36	2.01	1.05	1.15
1991–2001	1.02	1.09	1.50	1.68	1.98	1.81
2001–2007	1.56	1.44	1.05	0.56	1.73	1.82
1961–1981	2.31	2.62	1.43	1.58	1.16	1.17
1981–2007	1.22	1.08	1.78	1.55	1.62	1.56
1981–2013			1.55	1.53	1.68	1.52
1961–1991	2.20	2.03	1.72	1.72	1.20	1.17
1991–2007	1.16	1.22	1.33	1.26	1.71	1.81
1991–2013			1.12	1.31	1.77	1.70
1961–2007	1.82	1.75	1.79	1.56	1.40	1.39

Notes: All figures are annual average growth rates. “OLS” refers to estimates computed by regression of productivity indexes in logarithms against a time trend variable over the relevant interval; “Mean” refers to the average of year-on-year growth rates during the relevant interval.

Source: Calculated by the author using data from InSTePP (Version 5 of the InSTePP Production Accounts), USDA-ERS (2015) and USDA-ERS (2016).

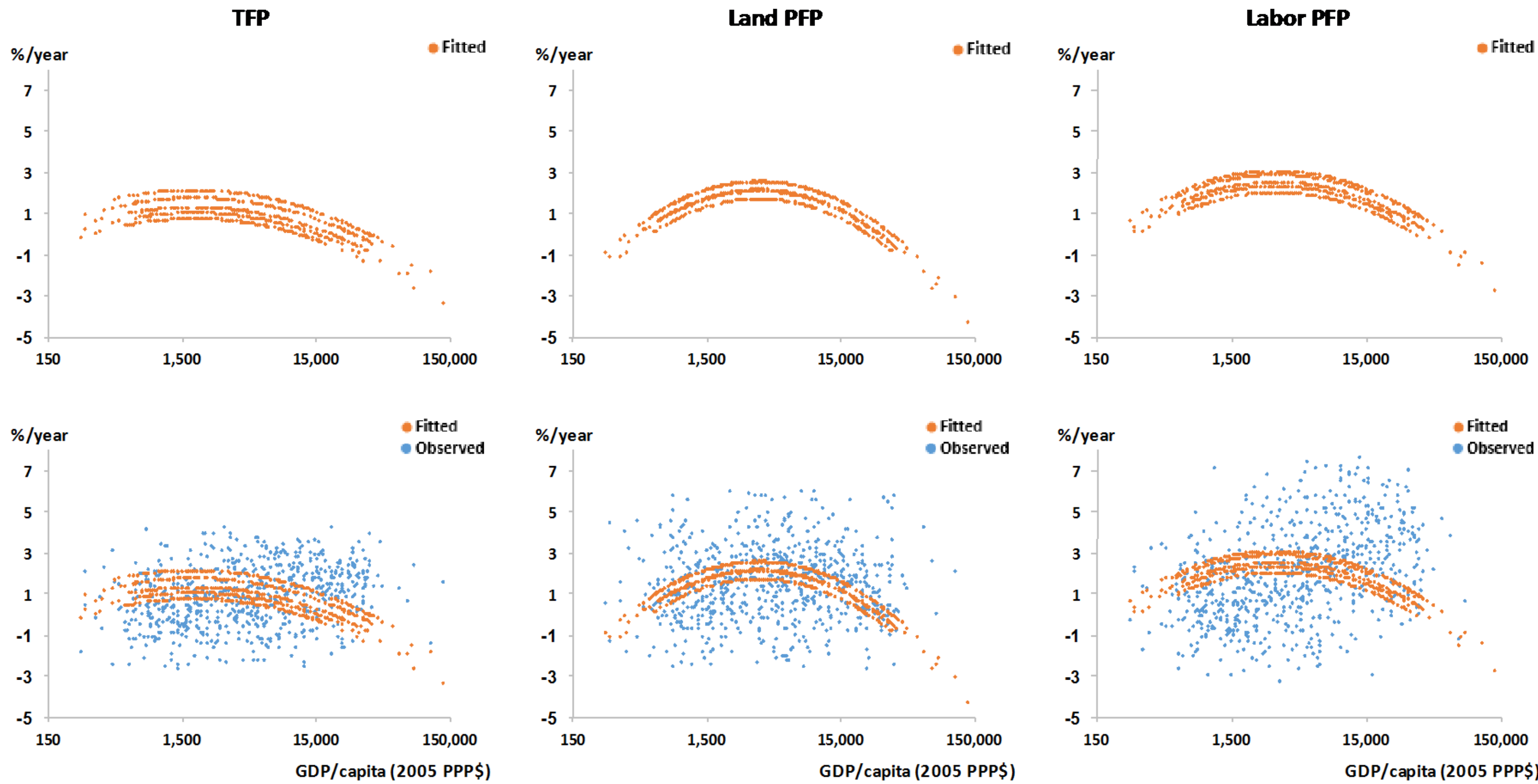
Appendix Table A-1
Changes in U.S. Agriculture, 1929–2017 (five-yearly)

Year	VASP (2009 $ billion)	NFI (2009 $ billion)	100* (NFI/VASP) (%)	Number of Farms ('000)	NFI/Farm (2009 $/farm)	Land in Farms (million acres)	Farm Size (acres per farm)
1929	**139. 6**	**62.1**	**44.5**	**6,512**	**9,543**	**974.3**	**149.6**
1930	117.7	44.7	38.0	6,546	6,831	990.1	151.3
1935	124.1	66.7	53.7	6,814	9,787	1,054.5	154.8
1940	130.7	55.2	42.2	6,350	8,687	1,065.1	167.7
1945	239.0	119.4	50.0	5,967	20,018	1,141.6	191.3
1950	238.8	99.3	41.6	5,648	17,579	1,202.0	212.8
1955	213.6	72.6	34.0	4,654	15,605	1,201.9	258.3
1960	216.3	64.0	29.6	3,963	16,151	1,175.6	296.7
1965	235.2	68.8	29.3	3,356	20,506	1,139.6	339.6
1970	241.3	62.9	26.1	2,949	21,332	1,102.4	373.8
1975	317.4	81.2	25.6	2,521	32,195	1,059.4	420.2
1980	332.7	36.3	10.9	2,440	14,873	1,038.9	425.8
1985	267.5	49.7	18.6	2,293	21,683	1,012.1	441.4
1990	282.0	69.2	24.5	2,146	32,251	986.9	459.9
1995	270.0	52.8	19.5	2,196	24,022	962.5	438.3
2000	266.8	61.9	23.2	2,167	28,565	945.1	436.2
2005	298.0	85.6	28.7	2,099	40,800	933.2	444.7
2010	339.9	76.2	22.4				
2015	389.9	73.5	18.9				
2017	**351.6**	**54.8**	**15.6**				

Source: Based on data from USDA (2017) and InSTePP (Version 5 of the InSTePP Production Accounts)

Appendix Figure A-1

Regression models of a surge in international agricultural productivity, country-specific average data by decade 1961–2014



Source: Author's estimates of fitted values from Table 2, and observed values from FAOSTAT and USDA (2016).

Notes: Estimates from models including country and time fixed effects.