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Comment Brian Davern Wright

I have removed discussions of some issues included in my conference remarks that have been addressed in a subsequent revision by Alston and Pardey. For acknowledgments, sources of research support, and disclosure of the author's material financial relationships, if any, please see https://www.nber.org/books-and-chapters/role-innovation-and-entrepreneurship

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The US agricultural sector offers a fascinating and possibly unique case for study of sectoral innovation. The production technologies, factor proportions, and the productivity of the sector have been radically transformed by waves of innovation. However, the principal food and fiber products supplied at the farm gate, and the competitive organization of farms as the managerial units that produce them, have changed relatively little over the past century, so that comparable data on production, prices, and input use are available spanning an unusually extended period. Hence we have the opportunity to observe waves of research, innovation, and diffusion in a highly dynamic sector in the short and long views. A shelf containing all of Alston's and Pardey's highly cited books on the topic would need to be wide and sturdy. They are eminently qualified to meet the challenge of covering this multidimensional topic in a single chapter, for an audience not necessarily familiar with key elements of the story.

Figure 3.1 in Alston and Pardey (chapter 3, this volume) offers a dramatic illustration of one aspect of the story. For almost a century, beginning in 1850, farmland and farm families increased apace. This ended around 1936, when the number of farm families began a steep and persistent descent.[1] Then, as argued by Alston and Pardey, a 40-year productivity surge started in the 1950s and lasted for four decades.

Subsequently, they argue, a decline in public research intensity (relative to farm GDP) reduced farm productivity growth. Private agricultural research spending has risen to pass public funding, but it is focused on applied research and especially development expenditures off-farm, which does not generally compensate for the effect of reduced public support for research related to farm productivity.

Many observers of the trends in farm area and farm numbers embrace a very different narrative. Family farms, the backbone of US productivity, increased at a relatively constant size behind an expanding frontier through the mid-1930s. Subsequently, larger corporate oligopolies have been driving families off most off their land, relegating them to a low-income, impoverished rural fringe or to urban slums. Productivity growth has become less sustainable as corporate substitution of chemicals and machines for family management and labor has taken its toll, and urban sprawl has taken some of the best land out of production. This narrative might seem all the more convincing to those who know that the published data vastly overstate the current number of minimally productive family farms.[2] In 2012, less than 4 percent of farms generated two-thirds of farm sales, while the bottom half

1. Although land area shown in the figure continued to increase through 1955, total cropped area was about the same in 1936 and 1955. https://www.ers.usda.gov/data-products/major-land-uses.aspx (last accessed May 15, 2020).

2. US Department of Agriculture (2015, p. 1).

shared less than 1 percent. This might seem consistent with the notion that large farm corporations are getting the lion's share, leaving family farmers to struggle for the scraps. If so, no wonder public support for agricultural research has declined!

At a time when we all have good reason for concern about many heart-rending social phenomena, let me assure you that the process as characterized in the above narrative should not be numbered among them. It is true that, for the majority of "farm families," farm income is trivial at best. Does this mean they are impoverished? Not at all. Beginning in the 1960s, average nonfarm income of most farm families has risen fast.[3] In 2014, only 2 percent of farm households were in the bottom half of all households in terms of *both* income and wealth. Most farm households are families of wealthy retirees (many of them former farmers), or families with large off-farm income who choose to live in a rural residence.

Furthermore, even the top 4 percent constitute 80,000 farms, the vast majority of which are family operations with negligible market power, even if incorporated for tax or other reasons. It is interesting that talk of farm size increasing always focus on land or output. Measured by the aggregate of management and other labor, farm size in the US has very different dynamics. Indeed, it has changed remarkably little on average in more than a century—and remains quite similar to farm size in other countries in which farm income is dramatically lower, including India and China.[4]

As the number of farm families has fallen and acres and output per farm have risen, the share of measured farm output in GDP had plummeted to about 1 percent.[5] As the authors note, this is largely an accounting phenomenon. Many products once included as farm output are now located elsewhere.

Nevertheless, the secular decline in labor used in production on farms is striking. Is this driven by innovation? The answer is yes, but the question is where. A third narrative takes a macro perspective. Wages in the US since the end of the Great Depression been set in the nonfarm economy. The increasing opportunity cost of farm managers and labor meant that other factors—land and capital—must be substituted for labor to raise its marginal productivity to approximate off-farm opportunities generated by off-farm innovation, with some adjustment lag. This would have happened, and the number of farm managers and agricultural laborers could have declined, even if total factor productivity in farming had not risen nearly as rapidly.

3. US Department of Agriculture (2014), table 10.

4. The persistence of the family organization of farming is a problem for those who see Adam Smith's extreme functional specialization as a key to increased productivity. Its advantage lies in the necessity for self-motivated labor and management in a dispersed and highly stochastic local environment. The extent to which this might change as information technology evolves is a very interesting question.

5. https://www.erata-producs.usda.gov/dts/ag-and-food-statistics-charting-the-essentials/ag-and-food-sectors-and-the-economy/ (last accessed May 15, 2020).

Advances in hydroponics and vertical farming notwithstanding, the business of growing plants for food, animal feed, or fiber remains located on farms. Alston and Pardey focus principally on innovations that raise the productivity of land, management, labor, water, and fertilizers in producing crops or animal products, or sustains existing productivity of plants and animals as pests and diseases evolve. Many of these innovations are relevant to farms in other countries with very different labor intensities. The US history of innovation in this line of business begins with the important work of selecting plant varieties, often taken by immigrants and prospectors from other lands, and choosing those appropriate for new local environments. The federal government helped, for example, by distributing seed samples via the Post Office. Evenson demonstrated that, in the nineteenth century, the key mechanical inventions for farming the newly settled lands originated with farmers or local blacksmiths, often members of farm families, subsequently to be perfected by engineering firms.[6]

Given this history, agricultural economists have become accustomed to the fact that major inputs used by farmers (land services, seed, draft animals, breeding animals, forage, and management) are sourced from within agriculture. They tend to expect that research and innovative activities likewise will be located in the sector.

The establishment of US agricultural education at the Land Grant Colleges by the Morrill Act of 1862, and later of federal support for State Agricultural Research Stations by the Hatch Act of 1887, signaled a commitment of public support specifically targeted at productivity-increasing agricultural education and research of direct use to farmers, insufficiently fostered by the atomistic competitive private farm sector. The result was a string of innovations that facilitated the transformation of agriculture in the twentieth century.

In a volume on the role of innovation and entrepreneurship in economic growth, the contributions of private entrepreneurship, government policies, and the patent system in the innovation called the "agricultural research station," and indeed, the necessity and feasibility of public support, are questions worthy of a little further discussion. US agricultural experiment stations as public initiatives deserve the attention that the authors give to them. However, the initial motivations for the development of the idea of the agricultural research stations are complex.[7]

Consider two key figures. The first is Justus von Liebig, the son of merchant who compounded and sold paints and dyes, who has been called the founder of the modern chemistry laboratory. He experienced the "year without summer" in 1816 as a 13-year-old boy and became a chemist interested

6. Evenson, personal communication with author, 1993.

7. For a wide-ranging international perspective on this, and more detail on the influence of von Liebig, see Pardey, Roseboom, and Anderson (1991).

in agriculture. His education included study in the private laboratory of Gay-Lussac under a grant from the Hessian government. As professor at the state University of Geissen, in 1840, he authored the pioneering publication, *Organic Chemistry in its Relation to Agriculture and Physiology*. He founded his research laboratory as an initially private initiative, with the approval of his university. His experiments identified the role of nitrogen as a plant nutrient, and he influenced the competitive development of agricultural research stations in other states that would later become part of a unified Germany; by 1873, there were 25 such stations. He proclaimed the famous "law of the minimum" regarding the constraints imposed by available nutrients on plant growth. Besides his innovation of the modern chemistry laboratory and methods of teaching chemistry, von Liebig also developed key instruments for chemical analysis. His later applied research included the use of silver to replace the toxic mercury used in the making of mirrors. Although he was essentially an academic, some of his work was more entrepreneurially oriented. For example, his research on meat enabled the private sector development of what became Oxo beef cubes.

Consider, in contrast, John Bennet Lawes, a land-owning entrepreneur interested in chemistry applied to agriculture. Having learned some chemistry as an undergraduate at Oxford, he prematurely returned to Rothamsted Estate, which he had inherited as a boy, on the bankruptcy of its tenant. Around 1837, he began small experiments on ammonium salts as nitrogen fertilizers, and he identified ammonium phosphate as producing the greatest yield increase in cabbages. Further experiments resulted in the production of a highly effective phosphate fertilizer, succeeding in competition with von Liebig (founder of the chemistry laboratory), by treating phosphatic minerals with sulphuric acid. He patented his invention of superphosphate (Patent 93530) in November 1842. In 1843, he hired Dr. J. Henry Gilbert, who had studied under von Liebig in 1840, to manage his laboratory, and constructed what has been called the world's first fertilizer factory (Warington 1900). A few years later, he purchased another related patent from a competitor. His factory marked the highly successful commercial beginnings of a fertilizer industry that became established as the major customer for sulphuric acid.

Lawes' Rothamsted Experimental Research Station was no doubt a useful complement that encouraged growth of his highly successful fertilizer business. His subsequent endowment of Rothamsted furnished the base for its continued operation today as the oldest agricultural research station in the world.

The establishment of Rothamsted affected the development of the US Land Grant Universities. For example, Evan Pugh, who had worked at Rothamsted in 1857–59 on the sources of nitrogen for plants, became the first president of the new Pennsylvania State University. In the 1920s, R. A. Fisher, as head of the statistics department at Rothamsted, transformed experimental agricultural research with his work on analysis of variance

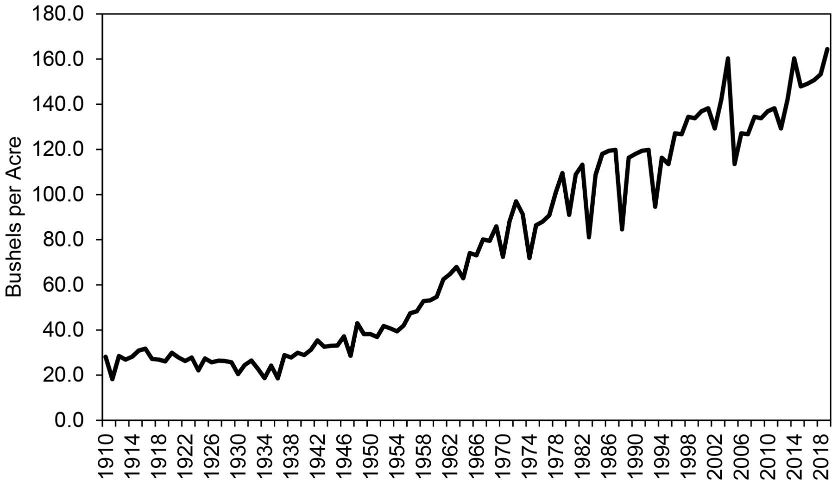

Fig. 3.C.1 US corn yield
Source: USDA, ERS, 2019.

and experimental design. However, the German experiment stations in the tradition founded by von Liebig around 1840 had greater influence on the design of the US public agricultural research effort (Finlay 1988). The first director of a US agricultural experiment station, Samuel W. Johnston, was trained by a founder of the German system.

What was the effect of this US research effort on the productivity of US crops? Yield per acre is one relatively straightforward indicator, even though the contributions of complementary inputs, such as fertilizer and irrigation, should properly be considered. Let us focus on yields of corn and domestic wheat. Both are grasses, but one is an open-pollinating diploid, the other a self-pollinating hexaploid. Nothing outstanding happened to their average national yields for nearly a century. Then, as shown in figures 3.C.1 and 3.C.2, during the mid-1930s, yields of both began an increasing trend that in the past six decades has displayed an approximately constant arithmetic rate, consistent with Malthus' assumption about the nature of technical progress.

How can we explain the beginnings of such persistently higher trends in yields in the 1930s? There is no obvious common biological or entrepreneurial element. For corn, the increasing yield coincided with introduction of hybrid varieties. Seeds produced from hybrid parents have a yield disadvantage that discourages farmers from replanting their output. Under this protection commercial firms, notably Pioneer Hi-Bred, came to dominate breeding, production and sales of hybrid seed, but not more basic research. In wheat there was no such abrupt change in the breeding strategy and no sustained shift to commercial breeding.

A third crop, soybeans, became a major complement to corn as its yield

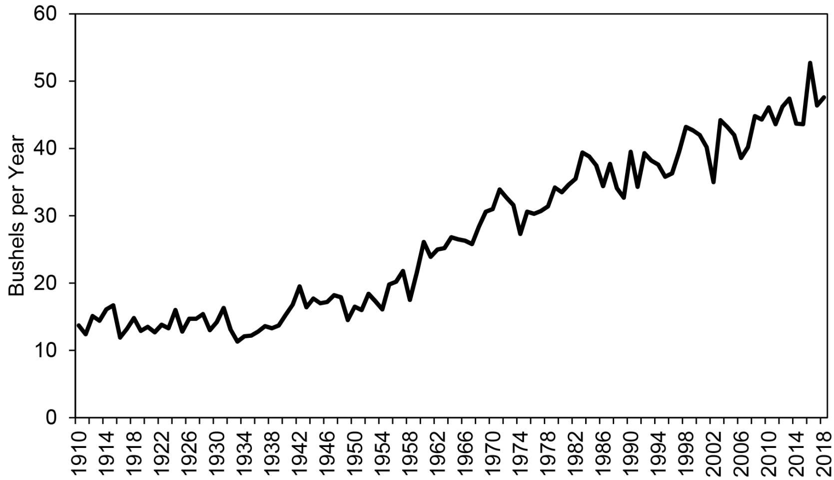

Fig. 3.C.2 US wheat yield
Source: USDA, ERS 2019.

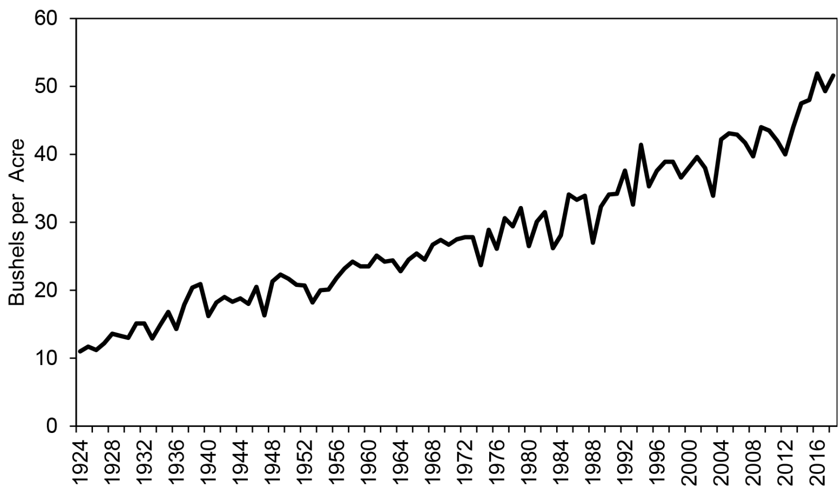

Fig. 3.C.3 US soybean yield
Source: USDA, ERS, 2019.

increased, also at a relatively constant arithmetic rate, starting a little earlier (figure 3.C.3). This was a very different crop, a legume supplied with atmospherically derived nitrogen via symbiotic bacteria, and hence lacking the potential response to nitrogen fertilizer inherent in corn or wheat, which generated research opportunities in both crops.

With these yield histories in mind, look again at figure 3.1 of Alston and

Pardey. They identify the productivity surge as starting in 1950. But the number of farm families began to fall fast in the mid-1930s. Some of this fall is related to the ending of the Great Depression and the re-emergence of urban employment opportunities. Even so, it is remarkable that in the mid-1930s, the yields of both crops began to increase persistently (figures 3.C.1 and 3.C.2). Could this be the true date of the beginnings of the productivity surge discussed by Alston and Pardey? Could Fisher's work on design and analysis of crop experiments have a role in the sharp discontinuity in yield gains for wheat and maize?

The postwar public agricultural research expenditures also increased monotonically (Alston and Pardey's figure 3.5b) until the downturn in expenditure intensity in the new millennium. Figure 3.6b shows that research intensity per unit agricultural GDP also increased remarkably. In reading the chapter, it is easy to miss the fact that public inputs into agricultural research were not only high relative to other sectors but were also increasing fast through the millennium.

Crop yields have continued to increase as agricultural research intensity waxed and waned.[8] This might well partly reflect the long lag of the returns to agricultural research. Alternatively, crop research intensity might not be well aligned with agricultural research intensity. This could be true; the authors are uniquely equipped to tell us. An alternate conjecture might be that the correlation of yield changes with research intensity might be spurious: public research might not be a proximate determinant of yield increase.

Private research intensity had surpassed public by the new millennium, mainly focused on innovations in fields that the authors classify as in the agricultural sector but are currently outside the farm sector. Measures of private research intensity must depend heavily on the components counted in the numerator and in the denominator. This is a daunting task. There seems to be no consensus as to the definition of private agricultural research, and the authors have no doubt spent a lot of time and effort on getting it right. Clancy et al. (2020) include animal health, biocides, fertilizers, agricultural machinery, agricultural plants, and agricultural research inputs. Graff et al. (2020) define the fields of agricultural venture capital as online businesses, software, commodity processing, and agricultural research inputs. They find that only 2 percent of all the firms included in at least one of three sources of venture capital startups in agriculture, PitchBook, VentureSource, and Crunchbase, appear in all three databases.

I wonder whether the effort to locate relevant research in and outside the agricultural sector might seem a little puzzling to economists who spend most of their time on other sectors of the economy. A century ago, most agricultural research was public, much of it actually located on (experimen-

8. In particular, wheat figures might be complicated by changes in area planted and average land quality, perhaps affecting average yield in recent years.

tal) farms and directed at familiar and clearly agricultural processes. "Spillovers" from other sectors were exceptional. Now most off-farm research is less obviously restricted to agricultural users and more difficult to relate to specifically agricultural off-farm activity. In this sense, is the agricultural sector becoming more like most of the rest of the economy?

Finally, let us turn to the key question of the returns to public agricultural research. Historically, calculation of returns to agricultural research was particularly important, because there was thought to be a need to justify public expenditures to taxpayers as well as to farmers. Farmers have recently become less interested in public expenditure on research as a source of increased wealth. They understand more clearly that most of the benefits accrue in the long run to consumers at home and abroad. Further, they have learned that returns to lobbying for favorable market distortions have a much larger payoff. US grain farmers gained greatly from biofuels mandates enacted in 2005 and 2007 that resulted in the speedy diversion of around 30 percent of the feed value of the US corn crop to biofuels, effectively eliminating the effects of a decade or more of progress in corn yields (Wright 2014). The gains in income and land values were far beyond the most optimistic predictions of the financial benefits farmers might get from keeping agricultural research intensity on track.

There is no doubt that overall, the social returns have been very good for the nation as a whole, with spillovers worldwide. But problems arise in measuring those returns. The authors allude to problems with the internal rate of return, a topic that they have pursued in greater depth elsewhere, and prefer benefit-cost ratios. However, benefit-cost ratios are also problematic. High benefit-cost ratios may well be useful in the quest for political support for public agricultural research. Unfortunately, these ratios can be manipulated. As long as the ratio is above unity, reclassification of costs as negative benefits, or vice versa, can get you a number close to unity, or as high as you like.

For allocation of research dollars across and within sectors, high average returns as indicated by benefit-cost ratios are not sufficiently informative. We would like to use measures more relevant to identification of marginal and submarginal projects, or better yet (if feasible), the marginal productivity of resource allocation in each project. Perhaps the relatively constant yield increases for three major crops over a long period reflects the fact that long-run programs in this area (including private sector research on corn in particular) are thought to be about the right size and have been protected as the attractiveness of other public opportunities for allocating marginal research dollars has recently declined, justifying some reduction in funding of such opportunities, and a reduction in overall research intensity? After decades of careful data collection and illuminating research, the authors are well qualified to address this question.

For any measure of returns to research investment, a widely acknowledged problem is posed by the long and variable lags. Even 150 years of data are not sufficient to identify the correct lag structures, and controlled experiments to answer the question are not feasible. Another obvious but unavoidable difficulty is that empirical studies are of necessity retrospective, and so of limited utility for high-level decisions on research plans for a changing world. Nevertheless, careful construction, maintenance, and analysis of data sets (exemplified by the work at InSTePP) are crucially important tasks. Building on this knowledge base, decisions on resource allocations to agricultural research must rely on informed reviews of perceived needs and potential technical and economic opportunities based on the state of the art, as exemplified in this chapter.

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