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ABSTRACT

Feeding the world's growing population is one of the most critical policy challenges for the 21st century. With tightening constraints on water, arable land, and other natural resources, agricultural innovation is quickly becoming the most promising path meet the nutrient needs for future generations. At the same time, the increasing variability in the world's climate intensifies the need for developing new crops that can tolerate extreme weather. Despite the urgency of this task, there is an active discussion on the returns to public and private spending in agricultural R&D, and many of the world's wealthier countries have scaled back their share of GDP devoted to agricultural R&D. Dwindling public support leaves universities, which, historically, have been a major source of agricultural innovation, increasingly dependent on funding from industry, with uncertain effects on agricultural research. All of these factors create an urgent need for systematic empirical evidence on the forces that drive research and innovation in agriculture. This book aims to provides such evidence through economic analyses of the sources of agricultural innovation, the challenges of measuring productivity, the role of universities and their interactions with industry, and emerging mechanisms to fund agricultural R&D.

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Over the last 50 years, mechanical, biological, and chemical innovations have more than doubled agricultural output while scarcely changing input quantities (Alston et al. 2010). In 1957, Zvi Griliches estimated that the internal rate of return for research on new corn hybrids was around 40 percent. A meta-analysis of R&D productivity estimates for 1965 to 2005 suggests even higher returns for those years, with a median estimate of 45 percent (Fuglie and Heisey 2007).

Yet, returns to agricultural R&D are exceedingly difficult to measure. Even when costs and benefits are known, creating accurate summary statistics can be challenging. For example, an analysis of 2,242 investment evaluations between 1958 and 2011 has found that calculating a modified internal rate of return (MRR) instead of the standard internal rate of return (IRR) is associated with an enormous decline in reported returns to agricultural R&D, reducing the estimated median annual return from 39 percent to less than 10 percent (Hurley, Rao, and Pardey 2014).[1]

Moreover, many recent studies find that returns to agricultural research have been declining of late. Anderson, Alston, Pardey and Smith (2018) document that US multifactor farm productivity grew at an annual average rate of 1.16 percent per year during 1990–2007, down from 1.42 percent per year 1910–2007. They also find that US yields of major crops grew at an annual average rate of 1.17 percent for 1990–2009 compared with 1.81 percent for 1936–1990. Similarly, an analysis of research inputs and total factor productivity (TFP) between 1970 and 2007 indicates that TFP growth declined slightly in agriculture, while effective research investments rose by a factor of two (Bloom, Jones, Webb and van Reenen 2019), suggesting that research productivity declined by a factor of nearly four, equivalent to an average decline of 3.7 percent per year.

Intensifying the potential threat of diminished productivity, the share of GDP to agricultural R&D has declined in many wealthy countries. In 1995, total global spending on agricultural R&D was around $33 billion. Roughly two thirds of this spending originated from

[1] Another potential issue is that some of the welfare benefits of agricultural innovation may accrue to consumers in the form of lower prices for agricultural goods. Low price elasticities of demand for agricultural products imply that productivity gains from freely accessible agricultural innovations reduce the price of agricultural goods (Guttman 1978), making consumers the primary beneficiaries of such innovations. With free trade and reasonable transport costs, these welfare gains diffuse across domestic and foreign consumers, reducing domestic consumers' willingness to pay.

governments, universities, and not-for-profits, while one third originated from profit-motivated R&D (Pardey and Bientema 2001). Five years later, by 2000, total global spending was roughly the same, but the share of public to profit-motivated R&D had changed to 60 and 40 percent (Pardey et al 2006), highlighting a growing reliance on industry funding for agricultural R&D.

The goal of this book is to provide new evidence on the potential impact of this shift from public to private sector funding and, more generally, to further our understanding of the returns to public and private spending R&D. Individual chapters examine the sources of agricultural knowledge and investigate challenges for measuring the returns to the adoption of new agricultural technologies, examine knowledge spillovers from universities to agricultural innovation and explore interactions between university engagement and scientific productivity. Analyses of agricultural venture capital point to that industry as an evolving source of funding for agricultural R&D. Methodologically, the research in this book spans the spectrum from archival research and text analysis to survey design and structural estimates. Discussions of each chapter outline promising directions for future research.

Tracing Agricultural Productivity to Its Source

In their chapter **The Roots of Agricultural Innovation: Patent Evidence of Knowledge Spillovers,** Matt Clancy, Paul Heisey, Yongjie Ji, and GianCarlo Moschini investigate knowledge spillovers from innovations *outside of agriculture* as a source agricultural innovation. While many previous analyses have investigated knowledge spillovers, nearly all of these studies have focused on spillover between different segments of agricultural R&D (e.g., Evenson 1989), or across states or countries (Alston 2002). This chapter extends prior studies in two major directions: 1) by examining spillovers from other industries into agriculture and 2) by introducing a new method to measure knowledge spillovers through text analyses.

Using the full text of US agricultural patents issued between 1976 and 2016, Clancy and his co-authors construct three complementary measures of knowledge spillovers: 1) citations to non-agricultural patents, 2) citations to scientific publications in non-agricultural journals and 3) a text-analysis algorithm that identifies "text-novel concepts" that are novel to agricultural patents but not to other technology fields. The authors apply these three measures to patents in subsectors of agriculture: animal health, biocides, fertilizer, machinery, plants, and agricultural research inputs.

Analyses of all three measures indicate that more than half of all patents in agriculture have benefitted from knowledge sources outside of agriculture. In three of the six subsectors—animal health, fertilizer, and machinery— more than half of all spillovers into agriculture appear to have originated from other industries. In "animal health," the share of outside knowledge among cited patents is extremely large, on the order of 90 percent. In only one subsector— plants—knowledge flows typically originate from agricultural R&D.

Non-agricultural sources of knowledge flows into agriculture are, however, rarely completely detached from agricultural research. For example, agricultural patents are more likely to cite scientific publications in biology and chemistry compared with publications in other journals. Agricultural patents are more likely to cite or share text-novel concepts with the non-agricultural patents of firms that have at least one agricultural patent in their portfolio.

The new text-analysis measure of spillovers is a major contribution of this chapter, and it introduces a useful complement to citations as a measure of knowledge flows. Methodologically, Clancy and his co-authors define "text-novel concepts" as words and phrases (strings) that are new in agricultural patents in the second half of their data (for patents with application years between 1996 and 2018). First, they identify roughly 100 text-novel concepts in each of the six subsectors. Then, they search all US patents in other sectors (outside of their six subsectors) for prior mentions of these concepts. For example, the string "pyrimethamine" does not appear in any animal health patents before 1996 but is a common term in animal health patents afterwards, making it a text-novel concept. When earlier patents on human health mention pyrimethamine their measure records an incidence of knowledge spillovers from human health to animal health.

Using these measures, the authors identify several areas in which findings from citation-based measures may be misleading. In biocides, for example, most patents cite non-agricultural patents and journals, which suggests that most spillovers originate from other disciplines. Using the measure of text-novel concepts, however, the authors show that these concepts are never mentioned in earlier patents outside of biocides, which indicates that they may have originated in biocides. More generally, they find that citations-based measure of knowledge spillovers, which have been used as the standard measure of knowledge spillovers, may overstate the share of knowledge spillovers *within* agriculture relative to text-based measures.

Their discussant Alberto Galasso emphasizes that these findings have important implications for our understanding of how shocks propagate through the economy through industry linkages (Barrot and Sauvagnat 2016). He also suggests a potential refinement for estimates of knowledge spillovers, by controlling for the size of technology fields. A relatively small field like animal health may appear to draw more knowledge from a large field, like chemistry, simply because chemistry is a very large field; controlling for field size will address this issue. Galasso further highlights the importance of distinguishing involuntary spillovers from intentional knowledge transfer through licensing contracts between non-agricultural and agricultural firms. This concept is picked up and extended in later chapters on knowledge flows between universities and industry.

Selection as a Challenge for Measuring Returns to Biological Innovation

A chapter by Jared Hutchins, Brent Hueth, and Guilherme Rosa on **"Quantifying Heterogeneous Returns to Adoption of Genetic Technology: The Case of the Dairy Industry**" uses individual (cow-) level micro data on milk production in a structural model to estimate the impact of genetic selection. The dairy industry has experienced a 3-4 percent increase in milk yields per year; half of this increase has been attributed to genetic improvement in the quality of bulls. Yet, the match between the bull and the dame (the mother of a new cow) may be just as important as the quality of the bull. Such selection is a common problem in estimating returns to agricultural innovation. For hybrid corn, for example, a substantive share of the increase in yields after the adoption of hybrid corn is due to the fit between the hybrid seed and its most productive environment, as Griliches (1957) has shown for the early 20th century United States and Suri (2011) for modern-day Kenya.

Observing and identifying selection in the dairy industry, however, is difficult because success takes several years to observe. For corn, the success of a new match can be observed within the season. Cows, however, take three years to mature before they produce milk. This delay between the matching of a dame and a bull and the breeder's ability to observe the milk production of their offspring is simply too long to allow for experimental learning. As a result, genetic improvements in dairy occur gradually through an endogenous process of selection that is mediated by demand and supply.

Hutchins, Hueth, and Rosa estimate the contribution of this selection process using detailed data on the "genetic merit" of individual bulls from the Dairy Herd Improvement (DHI) program. Going back to 1908, this program of the US Department of Agriculture covers roughly half of all dairy herds in the United States. Widely adopted since the early 1960s, artificial insemination technologies have created unprecedented opportunities to observe the performance of bulls, who can now produce thousands of offspring. Every daughter of a bull contributes new data, improving estimates of milk production associated with his genes. The authors exploit these data to estimate a structural model of genetic improvement and selection in the form of assortative matching between a high-value cow and a bull.

Estimates from a structural model of returns to high-yield genetics imply that 75 percent of these returns are driven by selection, in the form of assortative matching. Exploiting animal-level data the authors show that productivity gains are driven by matching at the level of animals and not just at the farm. In other words, they show that productivity in dairy has increased not only because better farmers choose better bulls, but also because farmers match productive cows with productive bulls.

These findings indicate that farmers are critical to determining the returns to biological innovation today. This is similar to the role they played in US innovation historically when farmers often discovered new varieties of food and feed crops. Olmstead and Rhode (2008), for example, examine the challenges that informational problems and cross-fertilization created for innovations by private farmers and breeders in cotton. According to Robert Evenson, until the end of the 19th century, all crucial mechanical inventions in agriculture were the work of farmers and local blacksmiths, rather than of large cooperation (cited in Wright 2012, p. 1718).

Paul Scott's discussion places the findings of Hutchins, Hueth, and Rosa in the context of the econometric literature on the correlation between producer's input decisions and unobserved productivity (which reaches back to with Marshak and Andrews 1944). Scott first outlines the properties of plausible instruments to assess the effect of selection on the measured productivity of bulls. Specifically, he suggests using the change in a bull's ability to transmit favorable genes to produce protein or butter fat (the Predicted Transmitting Ability, or PTA) as an instrument for the bull's PTA. Using this instrument, the authors find that there is still evidence of selection based on unobserved productivity differences. Scott points out that other choice variables, such as herd size and the frequency with which farmers milk their cows may also be correlated with PTA values. In principle, all of these endogenous explanatory variables need additional instruments. Even though these concerns may be partially addressed by improved measures of genetic traits in the future, the selection problem raised by this chapter remains relevant, due to unobservable characteristics and choices of individual farmers.

Innovation as a Response to Environmental Shocks

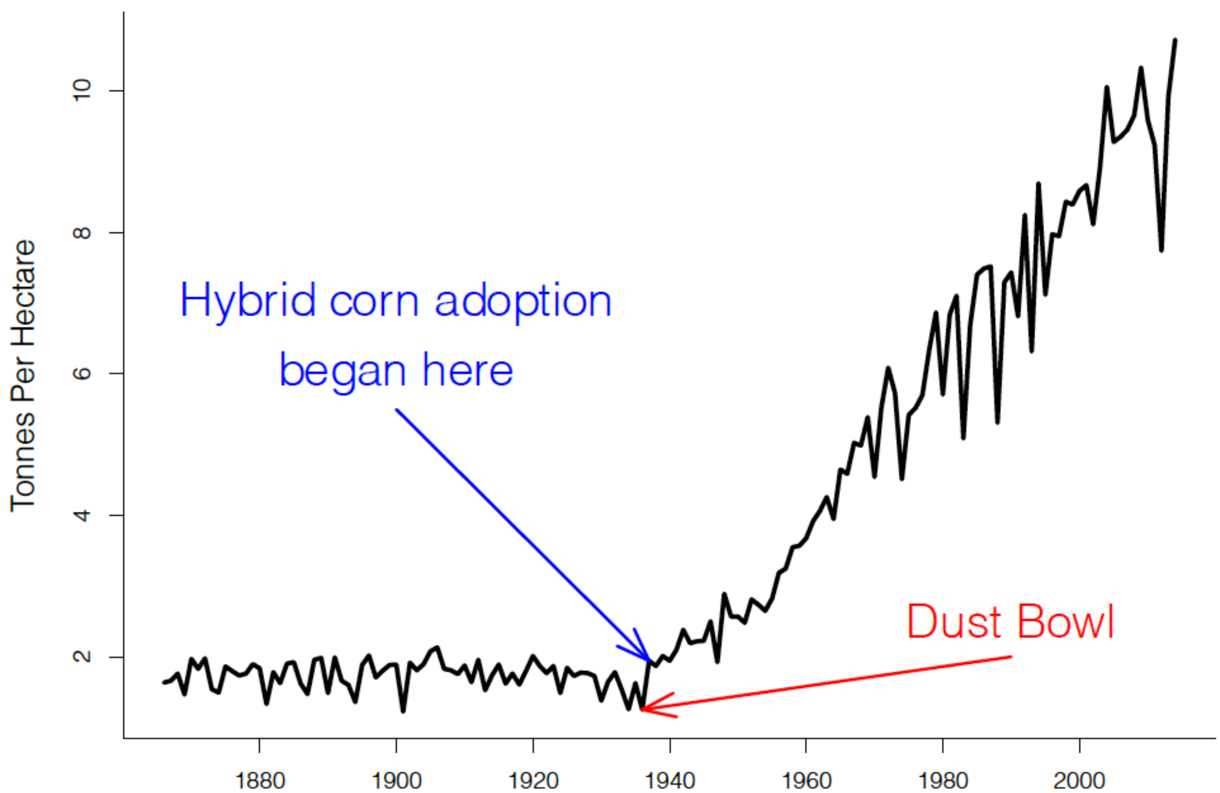
Expanding on theme of farmers' role in selecting the most productive technologies, a chapter by Keith Meyers and Paul W. Rhode examines farmers decisions to adopt heat-resistant corn hybrids after a series of catastrophic droughts and harvest failures in the 1930s. In "**Yield Performance of Corn under Heat Stress: A Comparison of Hybrid and Open-Pollinated Seeds during a Period of Technological Transformation, 1933-1955,"** Keith Meyers and Paul W. Rhode use newly recovered data from the archives of Zvi Griliches to re-examine the diffusion of hybrid corn seeds immediately following the Dust Bowl (1930-36).

Hybridization, which creates a new variety by crossing two corn (so-called filial F1) varieties, provided a new method of developing higher yielding and more resilient seeds. Compared with the traditional open-pollinated seeds (which are simply allowed to propagate in the fields), hybrids yield more corn and take less time to mature. They also have stronger roots and thicker stalks which makes them less susceptible to breaking in wind or rain, they are more resistant to disease, and they are more likely to survive a drought. Yet, hybrid seeds also cost more than open-pollinated seeds (Olmstead and Rhode 2008), and farmers cannot save hybrid seeds from their harvest to plant in the following year, because the offspring of saved seeds return to the characteristics of the parental varieties (instead of exhibiting the desirable traits of the purchases hybrid seed). As a result, farmers who switch to hybrid seeds must buy new seeds from the breeder every year, instead of building their own supply. These tradeoffs led to an uneven adoption of hybrid corn, which Meyers and Rhode re-examine in their chapter.

Griliches' (1957) showed that expected improvements in hybrid yields drove the adoption of hybrid corn in the Corn Belts and the Great Plains. Yet, Meyers and Rhode note, Griliches may have overlooked a significant link between the adoption of hybrids and a period of devastating droughts and crop failures during the Dust Bowl years of 1934 and 1936. Narrative historical evidence suggests that corn farmers learned about the benefits of planting drought resistant hybrids by observing neighbors' crops failing or surviving during these droughts. The late Richard Sutch (2011) argued that drought resistance became more salient to farmers as a result of climate shocks, and he highlights the role of the U.S. Department of Agriculture to promote hybrid seeds after the Dust Bowl.

In fact, hybrid corn gained its most substantial foothold in US agriculture in 1937, just one year after the catastrophic harvest failures of 1936 (Figure 1) and was planted on more than 40 percent of corn acreage in the most productive counties of Iowa and Illinois.

FIGURE 1 – U.S. CORN YIELDS 1888-2014



Notes: From Michael Robert's discussion of Meyers and Rhode (2020), using data on corn yields from the USDA's National Agricultural Statistics Service (https://www.nass.usda.gov).

To investigate whether hybrids did in fact mediate the effects of weather shocks – in the form of extreme heat and drought - Meyers and Rhode have returned to Zvi Griliches' archives to construct fine-grained geographic data on hybrid corn adoption and yields, matched with historical data on droughts. While existing analyses rely on state-level data, this substantial effort of data collection allows Meyers and Rhode to examine adoption patterns at the level of crop reporting districts (CRDS), roughly the size of 10 neighboring counties. This analysis indicates corn breeding allowed the corn frontier to move further North, into Canada. Focusing on heat tolerance as a measure for tolerance to droughts, Meyers and Rhode show that hybrid corn grown in Iowa from 1928 to 1942 did exhibit heat tolerance relative to open-pollinated varieties, consistent with the findings of Richard Sutch. These results, however, do not replicate in other states, and reduced temperature sensitivity does not appear when comparing hybrid and open-pollinated yields grown in other states. This latter finding supports Zvi Griliches' decision to ignore drought-tolerance in his analysis of hybrid adoption.

Their discussant Michael Roberts is even more skeptical than the authors of the view that the adoption of hybrid corn was a response to the Dust Bowl and issues a stark warning about the limits of technical change in agriculture as a response to climate change. Schlenker and Roberts (2009), for example. have shown that the number of extreme heat days above 29 Celsius is the best predictor of corn yields. Modern data indicate that high-yielding GMO varieties that are prevalent today are even more sensitive to extreme heat than the traditional varieties (Lobell et al 2011).[2]

In the 20th century, US agriculture was able to capitalize on vast productivity gains by developing plants with immense yield potential (the maximum output given available sunlight and light) and by creating varieties to match the available sunlight and water across the United States, while also processing massive amounts of nitrogen from fertilizers. Today, nitrogen is no longer a limiting factor, and the adoption of genetically modified crops (such as round-up ready corn) has made it easier to control weeds (roundup, or glyphosate) and pests (through BT strains). Yet, the large plants of today with their deep roots require more water, leaving modern varieties vulnerable to droughts. The unusually hot summer of 2012 approached the temperatures of the Dust Bowl. Current climate models predict many more summers like 2012, with even hotter temperatures. Roberts warns that innovation in corn and other crops may be unable to deal with extreme temperatures. Plants have reached the biological limits of photosynthesis, requiring an entirely new approach for a second Green Revolution.

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[2] Genetically engineered drought tolerance was introduced in corn hybrids in 2012 and became broadly available the following year. By 2016, 22 percent of total US planted corn acreage was drought tolerant. As the research of Richard Sutch as well as Myers and Rhode would suggest, adoption has been concentrated in drought-prone regions (despite the hybrids' limited ability to protect against the most extreme droughts, McFadden, Smith, Wechsler and Wallander 2019).

Recent advances in the emerging field of synthetic biology may offer a much-needed novel approach, by targeting improvements in photosynthetic efficiency. For example, a survey article by Batista-Silva et al (2020) discusses progress and challenges of engineering improved photosynthesis through synthetic biology as a potential path towards improving the utilization of solar energy and carbon sources to producer food, fiber, and fuel.

Universities as a Source of Agricultural Innovation and Productivity Gains

Publicly funded research has been a major source of innovation and advances in agricultural productivity throughout American history (e.g., Wright and Shih 2011, Olmstead and Rhode 2008). Since their foundation under the Morrill Land Grant Acts of 1862 (7 U.S.C. §301 et seq.) the original 52 land grant universities have been the key institution in creating and dissemination agricultural innovations (Wright 2012), establishing vital links between universities, farmers, and industry. With the 1862 act the United States government allotted 30,000 acres of federal land per state to finance the foundation of practically oriented research and training universities.[3] The 1887 Hatch act (7 U.S.C. § 361a et seq.) added research capabilities through the State Agricultural Experiment Stations, supported by grants of additional federal lands. In 1890, the second Morrill Act (7 U.S.C. §322 et seq.) increased the funding of these new colleges to $25,000 per year and specified that African Americans could receive education in existing land grant colleges and in new colleges designed for that purpose. Finally, in 1914, the Smith-Lever act established the Cooperative Extension Service to inform farmers about agricultural innovations and establish home instruction to help farmers learn about new agricultural techniques.

In its early decades of operation, the US land grant system supported agricultural productivity by encouraging the diffusion of European innovations. Evenson (1980), for example, documents that advances in agricultural productivity between 1870 and 1925 were strongly correlated with total real public spending on agricultural research during the preceding 18 years, but largely based on the adoption of European inventions. It took several decades, until the 1930s, for the system of land grant colleges and experiment stations to become an efficient source of domestic agricultural innovation (Huffman and Evenson 2006). Kantor and

[3] Southern state had originally opposed the Morrill Act and it only passed after the South seceded from the United States. As a result, none of the original 52 land-grant colleges operated in the South.

Whalley (2019) find that the establishment of agricultural experiment stations at existing land grant institutions through the Hatch Act of 1887 took between 20 and 30 years to increase land productivity in neighboring counties. Olmstead and Rhode (2002, pp. 931-32) show that, with the exception of early advances in corn, yields for field crops only began to increase after 1930. US wheat yields increased only 1.75 bushel per acre between 1866 and 1939, but increased by about 2.25 percent per year afterwards, doubling wheat yields by the 1970s.

Rosenberg and Nelson (1994) reason that the land grant college system was uniquely suited to resolve a fundamental tension created by industry funding for academic research. University research is typically "basic" research, aimed at understanding fundamentals, with payoffs that are often uncertain, distant, and exceedingly difficult to appropriate. By contrast, industry research targets specific problems and challenges with payoffs that are substantially more immediate and are expected to directly benefit the firm that funds the R&D. Due to this tension, many academics view industry funding as a direct threat to their research and academic integrity, as targeted problem-solving takes time from basic research, and sometimes even threatens open communications that are critical to academic exchange. According to Rosenberg and Nelson (1994) the institutional features of the land grant college, with a firm commitment to knowledge diffusion and the implementation of feedback from local users, are uniquely suited to easing the tension between basic and applied research, especially after the Smith Lever Act of 1914 provided funding for agricultural extension.

In **"Local Effects of Land Grant Colleges on Agricultural Innovation and Output,"** Michael J. Andrews estimates the effect of establishing a land grant college on invention and agricultural performance on surrounding locations. To make some progress towards identifying the causal effect of establishing a land grant college on invention, Andrews compare locations that receive a land grant college to "runner-up" counties that competed for establishing a land-grant college but ultimately lost. Comparing changes in patenting in college and runner-up counties after the establishment of a land grant college, Andrews shows that patenting increased in winning countries (compared to runner-up counties) after the establishment of a land grant college.

Patents, however, are an extremely noisy and potentially biased measure of agricultural innovations. Agricultural innovations of a chemical or mechanical nature were patentable throughout this period, while seeds and other types of biological innovations had no intellectual property protection. Moreover, even among innovations that were patentable, there were large differences in the share of innovations that inventors chose to patent across sectors and over time. An analysis of innovations exhibited at world technology fairs between 1851 and 1915 shows that roughly half of all agricultural machinery was covered by patents throughout this period (Moser 2012). By contrast, chemical innovations, were almost never patented at the beginning of this period and experienced a dramatic shift towards patenting after improvements in analytic methods reduced the effectiveness of secrecy, as an alternative to patents. Biological innovations first became subject to intellectual property rights through the US Plant Patent Act of 1930. Plant patents, however, are substantially narrower than utility patents, and they are limited to asexually reproducing plants (plants, such as apples and roses, that reproduce by roots, shoots, or buds), explicitly excluding plants that propagate through seeds, as well as tubers (Moser and Rhode 2012).[4]

To address these issues, Andrews uses historical data on the introduction of new wheat varieties from Clark, Martin, and Ball (1922) as an alternative, non-patent measure of innovation. This measure shows that land grant counties were about five times more likely to introduce a new wheat variety compared with runner-up counties after the establishment of a land grant college.

These findings are consistent with earlier research by Olmstead and Rhode (2002) that documents how the land-grant system helped to create and diffuse critical innovations in wheat, through the type of regional adaptive research for which the system had been designed. As the center of gravity of wheat production extended westward to less-favorable environments, breeders in the land-grant system identified and selected varieties that could tolerate drought, cold, insect pests, rusts, and other fungal diseases in these newly established growing regions.

[4] Using new varieties of roses as a non-patent measure of innovation, Moser and Rhode (2012) investigate whether the creation of plant patents in 1930 led to a significant increase in agricultural innovation. (Notably, most plant patents until the 1960s covered roses._ Data on registrations of newly-created roses indicates no increase in innovation after 1930: Less than 20 percent of new roses were patented, European breeders continued to create most new roses, and there was no increase in the number of new varieties per year after 1931. Instead, influential new varieties appear to have been a by-product of publicly funded research.

Investigating funding as a mechanism for encouraging innovation, Andrews shows that the effects of land grant colleges on local innovations was largest following the passage of legislation, such as the Hatch Act of 1887, which increased funding for agricultural research.

Turning to agricultural productivity, however, Andrews finds that, compared with runner-up counties, college counties experienced only small (and often negligible) improvements in agricultural productivity, measured by improvements in yields, crop output, or the production of livestock. Andrews explains that the productivity benefits of land grant research may have diffused beyond the borders of the college county, through a combination of outreach and university engagement (as described by Barham, Foltz, and Melo in this book).

Placing Andrew's results in the broader context of productivity spillovers suggests that the geographic diffusion of spillovers – beyond the county level – is a likely explanation for the weakness of county-level productivity effects. In a state-level analyses of productivity spillovers Alston et al (2010) show that over half the measured within-state productivity gains result from public research investments made elsewhere. Alston et al. (2010) estimate that the average marginal internal rate of return of public research accruing within the source state is 18.9 percent, significantly less than the estimated overall internal rate of return of 22.7 for the entire nation. Thus, the "failure" of the land grant system may lie in their focus on state-level agricultural priorities and a lack of specificity of their research to local (county-level) conditions, rather than in low productivity gains overall.

In his discussion, Bhaven Sampat highlights the usefulness of this chapter for the broader literature on returns from publicly funded research, which has held up the land grant system as a model of technology transfer that was more successful than the current, post Bayh-Dole system of patent licensing (Mowery et al 2004). Sampat also reminds us Brian Wright's (2012) positive assessment of the land grant system. Citing the findings of Olmstead and Rhode (2002), Wright (2012, p. 1719) reports that by 1919, more than three quarters of US wheat acreage used new varieties that had not been developed before the Morrill Act.

Sampat also points out that a strict focus on the diffusion of specific varieties may miss the contributions of universities, if academic research contributes research techniques and tools rather than new products. In the words of Griliches (1957) "hybrid corn was the invention of a method of inventing." Citing primarily Stackman et al (1967), Wright (2002, 1720-25) documents how research methods developed within the land grant system facilitated the development of new wheat varieties in Mexico after 1943 and supported research to improve rice in India and the Philippines. More recently, an analysis of drug development between 1985 and 2005 has shown that public sector labs *enable* two-thirds of marketed drugs, even though they only directly create one tenth of these new drugs (Sampat and Lichtenberg 2011).

Industry Engagement and Scientific Productivity

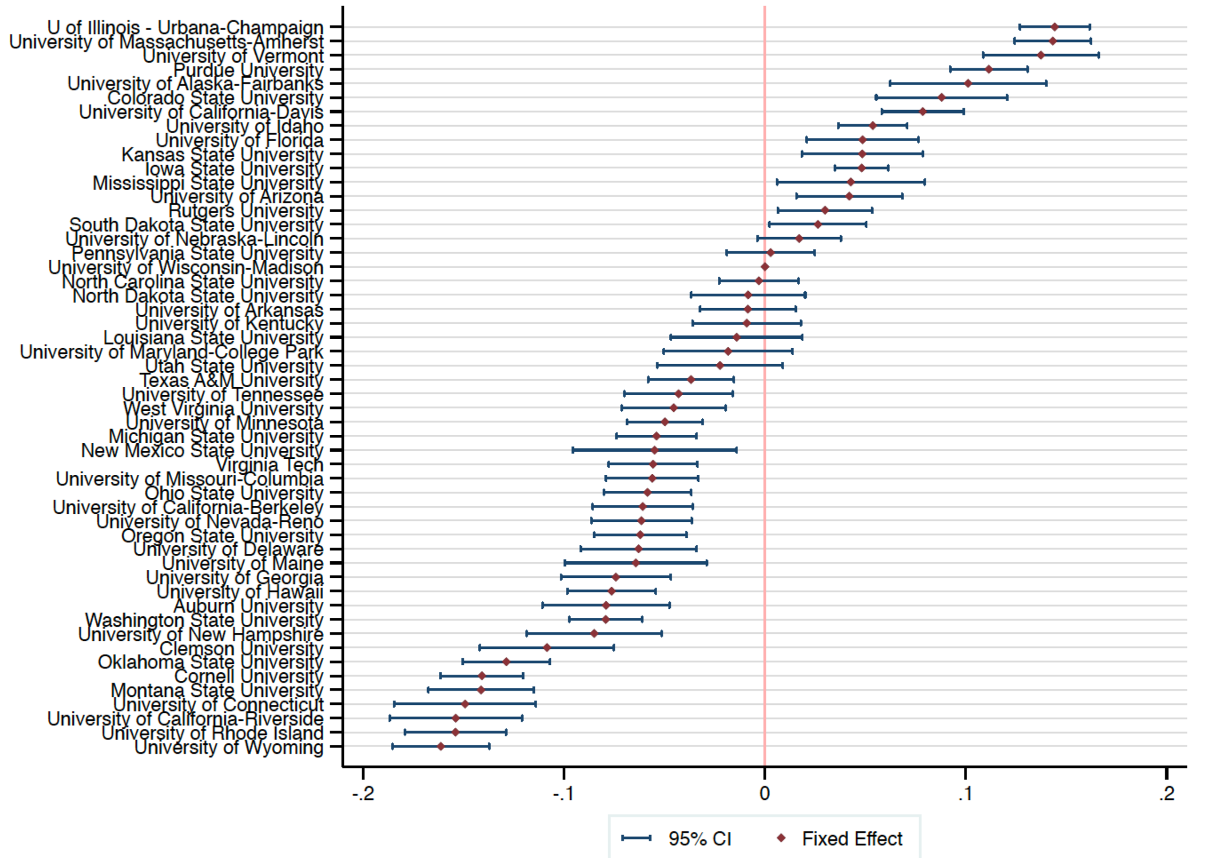
In their research on **"Academic Engagement, Commercialization, and Scholarship: Empirical Evidence from Agricultural and Life Scientists at US Land Grant Universities,"** Bradford Barham, Jeremy Foltz, and Ana Paula Melo examine links between industry funding and the activities, attitudes, and research choices of agricultural and life sciences faculty at land grant colleges. Their analysis focuses on two major questions: 1) what types of interactions are most likely to increase industry funding for faculty research, and 2) how does funding from industry influence the research of scientists? To answer the first question, the authors analyze two waves, conducted in in 2005 and 2015, of a survey of faculty at all 52 original land grant colleges. To analyze interactions between faculty and industry, the authors distinguish academic *engagement* (in the form of sponsored research, collaborations, and presentations) from *commercialization* (which includes patenting, licensing, and startups).[5]

Survey responses from faculty at land grant colleges reveal that academic engagement has generated between 15 and 20 times more research funding than academic commercialization. Engagement dates back to the land-grant universities' emphasis – since their inception in the 19th century – on practical agricultural and engineering sciences, formal extension appointments for faculty, and ongoing outreach with farms and firms to improve their performance. Dispelling the fear that engagement with industry crowds out research, the authors also find that faculty who are more engaged with industry publish more.

Notably, their surveys uncover important differences in the faculty-industry relations across universities (Figure 2), which suggests that institutional characteristics of universities play an important role in shaping links between academia and industry.

[5] This distinction is adopted to match recent papers on university-industry relations in Europe, such as Perkmann et al., (2013), Tartari et al., (2014); Tartari and Salter (2015), Sengupta and Ray (2017).

FIGURE 2 – UNIVERSITY-LEVEL PROBABILITIES OF FACULTY ENGAGEMENT WITH INDUSTRY



Notes: From Barham, Foltz, and Melo (2020). OLS estimates and 95 percent confidence for 52 university fixed effects (with the University of Wisconsin at Madison as the excluded category). The dependent variable is an indicator that equals 1 if a faculty member is engaged in any type of university-industry relations (UIR). Estimates control for gender, being a professor, and for having received a PhD from a land grant university. Standard errors are clustered at the university level.

As universities have been affected by dwindling state and federal support (e.g., Ehrenberg 2012) understanding sources of funding becomes critical. In principle, the passage of the Bayh-Dole Act in 1981 has created a new framework to commercialize innovations and discoveries associated with federally sponsored research (Sampat 2006, Thursby and Thursby 2011). Yet, the creation of stronger incentives at publicly funded institutions through Bayh-Dole appears to have failed its intended effects to encourage innovation. The findings of Barham, Foltz, and Melo suggest that, at least for the agricultural sector, the key institutions for university-industry relations had already been established in the 19th century through the US system of land-grant colleges.

Their discussant Nicola Bianchi emphasizes that this chapter is one of the most thorough analysis of university-industry relations to date, but also proposes promising directions for future research. For example, Bianchi points out that there is room to investigate the links between declining government grants and faculty involvement in university-industry relations. Follow-on research could also take advantage of publicly available sources on research output, including patents and publications to complement the chapter's rich existing data from faculty surveys.

Financing Future Innovations through Venture Capital

A final chapter on **Venture Capital and the Transformation of Private R&D for Agriculture and Food** presents a forward-looking analysis of recent trends in the financing of innovations. In this chapter, Gregory D. Graff, Felipe de Figueiredo Silva, and David Zilberman document the dramatic expansion of venture capital (VC) investments in agriculture startups, especially in the wake of the financial crisis of 2008. Between the early 2000s and 2018, VC investments in startups focusing on agricultural R&D increased from just tens of millions to more than seven billion. Notably, VC investment in agriculture startups increased not only in absolute terms but also relative to the overall supply of capital invested by the public sector and by public firms. To perform their analysis, the authors combine data from three proprietary data sources (Crunchbase, PitchBook, and VentureSource) to construct a new data set consisting of 4,500 startups in agriculture, with more than 10,000 financial transactions, including information on investments and exits.

Although, historically, private investment in agricultural R&D in emerging economies has been low (Pardey & Beintema 2001; Pardey et al, 2006), the authors report robust startup activities in in the larger emerging economies like India, China, and Brazil. In regression analyses, they examine potential causes for this shift, using data on 4,500 startups across 124 countries. Although the largest share of the startups in their sample operate in the United States (33 percent) and the European Union (23 percent), a significant share of the remaining 44 percent of startups are in emerging economies. Their regressions indicate that investments are strongly correlated with past liquidity events, suggesting that the expansion of VC investment in agriculture startups reflects a response to new investment opportunities in agriculture.

For a subset of these startups, their data also include information on investment and exit deals between 1981 to 2018. These data indicate that successful exits, in the form of Initial Public Offering (IPO) and Merger & Acquisition (M&A) led to higher investments by VC. Comparing different types of exits, the authors find that prior IPOs are associated with a stronger increase in investments than prior M&As. These findings are important for researchers and policy makers who aim to support agricultural innovation and R&D. Overall, the authors conclude that venture capitalists' willingness to invest may have been affected by an increase in the ratio of agricultural prices to non-agricultural commodity prices, highly visible exits of major players in the agriculture technology space, changes in agricultural labor markets, and advances in enabling (general purpose) technologies, such as cheaper genome sequencing, genome editing, or increasing data capacity of sensors and networks.

A discussion by Michael Ewens suggests promising directions for future research. First, Ewens suggests extending the existing results with an in-depth analysis of a single source. Such an analysis would address empirical challenges that result from variation in the coverage of agricultural VCs across the merged sources. Some of these analyses may require hand-collecting additional data, especially to expand the coverage of agriculture startups in emerging economies. Second, Ewens recommends additional analyses *within* agriculture to identify areas that grew differentially after 2008, using data on agricultural prices. For example, a potential extension would apply an empirical strategy implemented by Ewens, Nanda and Rhodes-Kropf (2018), which examines the effects of the cloud on VC in information technology. An extension to agriculture could exploit the effects of the same technology shock across different sectors within agriculture. Third, Ewens recommends examining the identity of investors, possibly by tracking the work histories of VC partners that choose to finance startups in agriculture. This question is particularly interesting and important because agriculture is a non-traditional investment for both VC and private equity.

Summing up

Importantly, the economics of agricultural innovation is even broader than the research included in this volume. While this book is focused primarily on agricultural innovation in the United States, a rich literature in development economics examines forces that drive the adoption of agricultural innovations (e.g., Foster and Rosenzweig 1995, Conley and Udry 2010, Suri 2011)

Other recent research has examined the effects of restrictions on the supply of farm labor on agricultural innovation, using historical restrictions on immigration as a source of exogenous variation (Clemens, Lewis, and Postel 2018, San 2020). These papers build on a long tradition of economic research on endogenous technical change reaching back to Hicks (1932). In fact, much of what we know about endogenous technical change has been learned in the context of labor-saving innovations in agriculture (e.g. Hayami and Ruttan 1970). These analyses range from the adoption of tractors in the first half of the 20th century to co-robots (machines that work alongside humans) that weed crops today and grafting robots that replace humans in the labor-intensive task of grafting herbaceous seedlings of fruits and vegetable crops (Gallardo and Sauer 2018).

Despite these omissions, the chapters in this book outline a diverse research that improves our understanding of agricultural innovation. This agenda spans several fields within economics, reaching from agricultural economics and economic history to finance and industrial organization. Authors of chapters, and their discussants, suggest promising opportunities for future research on the economics of agricultural innovation.

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