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Introduction

Petra Moser

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 (IRR) for research on new corn hybrids was around 40 percent. A meta-analysis of research and development (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 instead of the standard 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]

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[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 agricul-

Moreover, many recent studies find that returns to agricultural research have been declining of late. Andersen, 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 for 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 1936–90. 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 et al. 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 gross domestic product (GDP) to agricultural R&D has declined in many wealthy countries. Historically, the US public sector has been a top performer in worldwide agricultural R&D. This situation, however, has changed significantly in recent years, and the United States has lost its dominant position, falling behind China in 2009 through at least 2013 (Clancy, Fuglie, and Heisey 2016). In 1995, total global spending on agricultural R&D was around $33 billion. Roughly two-thirds of this spending originated from governments, universities, and nonprofits, while one-third originated from profit-motivated R&D (Pardey and Beintema 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.

This book provides new evidence on the potential impact of this shift from public to private sector funding and, more generally, furthers our understanding of the returns to public and private spending R&D. Measuring research and innovation is difficult in any field, but particularly in agriculture, and data constraints create major challenges for empirical analyses. To address these challenges, chapters in this book present original data sets ranging from text-based measures of innovation to animal-level data on dairy cow performance and fine-grained data on yields. Comments on these chapters discuss remaining measurement challenges and suggest promising directions for future data efforts and analyses.

Thematically, the chapters examine the sources of agricultural knowledge and investigate challenges for measuring the returns to the adoption of new agricultural technologies, survey knowledge spillovers from universities to agricultural innovation, and explore interactions between university engage-

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tural 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.

ment 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 a diverse spectrum, from archival research and text analysis to survey design and structural estimates. Yet all these individual contributions share some common traits. Several chapters use more fine-grained data than have been previously available to challenge prior findings (e.g., chapters 2 and 4) or resolve unanswered questions (e.g., chapter 3). Individual chapters use novel empirical methods to understand the sources of agricultural innovation (chapter 1), while others provide descriptions of important and new phenomena that are important for agricultural innovation (chapters 5 and 6). Chapters with a historical focus provide important insights that speak to our current challenges, such as agricultural adaptation to climate change. Building on this work, discussions for each chapter outline promising directions for future research.

I.1 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 sources of agricultural innovation. While many previous analyses have investigated knowledge spillovers, nearly all 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 by (1) examining spillovers from other industries into agriculture and (2) introducing a new method to measure knowledge spillovers through text analysis.

Using the full text of US agricultural patents issued between 1976 and 2016, Clancy and his coauthors construct three complementary measures of knowledge spillovers: (1) citations to nonagricultural patents, (2) citations to scientific publications in nonagricultural 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 research tools.

Analyses of all three measures indicate that more than half of all patents in agriculture have benefitted from knowledge sources outside of agriculture (figure I.1). 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.

Nonagricultural 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 nonagricultural 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 coauthors 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 afterward, making it a text-novel concept. When earlier patents on human health mention pyrimethamine, their measure records an incidence of knowledge spillover from human health to animal health.

Using these new text-based measures, the authors make two important points. First, they show that knowledge spillovers from nonagricultural sources are essential to agricultural innovation. Second, they find that citation-based measures of knowledge spillovers, which have been used as the standard measure of knowledge spillovers, overstate the share of knowledge spillovers *within* agriculture relative to text-based measures (figure I.1). Within the agricultural sector, the authors identify several areas in which findings from citation-based measures may be misleading. In biocides, for example, most patents cite nonagricultural 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.

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 nonagricultural and agricultural firms. This concept is picked up and extended in later chapters on knowledge flows between universities and industry.

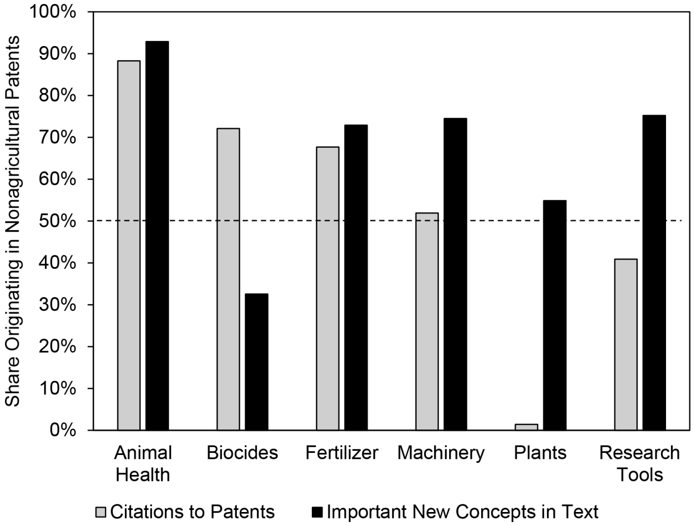

Fig. I.1 Knowledge spillovers into agriculture

Note: Knowledge spillovers into agricultural patents from other fields, measured through the traditional measure of *Citations to Patents* and the author's new text-based measure of *Important New Concepts in Text*. This latter variable captures concepts that do not appear in a given subsector before 1996 but become important afterward. The figure is based on data from chapter 1 in this book.

I.2 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 Genetic Selection: Evidence from Wisconsin Dairies" uses individual-level microdata on milk production in a structural model to estimate the impact of genetic selection. The dairy industry has experienced a 3 to 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 uniquely 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 (USDA) 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 the 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 corporations (cited in Wright 2012, 1718).

I.3 Innovation as a Response to Environmental Shocks

Expanding on the 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, 1933–55," Meyers and Rhode use newly recovered data from the archives of Zvi Griliches to reexamine 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 make 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 purchased 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 trade-offs led to an uneven adoption of hybrid corn, which Meyers and Rhode reexamine in their chapter.

Griliches (1957) showed that expected improvements in hybrid yields drove the adoption of hybrid corn in the Corn Belt 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 highlighted the USDA's role in promoting 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 I.2), and was planted on more than 40 percent of corn acreage in the most productive counties of Iowa and Illinois.

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 Griliches's 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 farther 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 Sutch (2011). 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 Griliches's decision to ignore drought tolerance in his analysis of hybrid adoption.

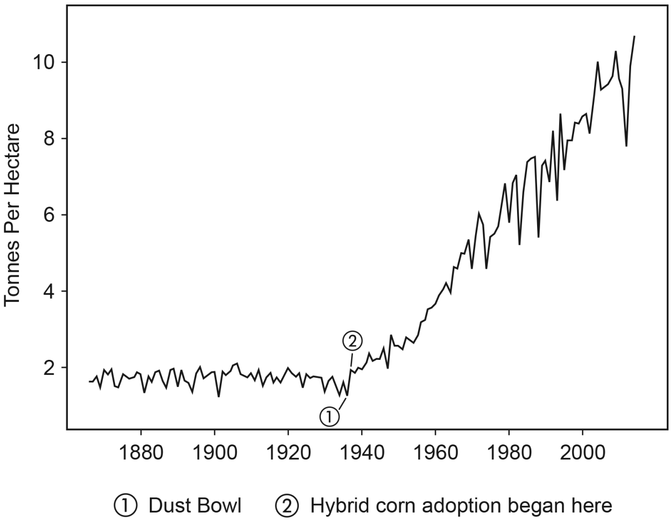

Fig. I.2 US corn yields, 1888–2014

Note: From Michael Robert's comment on the chapter by Meyers and Rhode in this book (see chapter 3), using data on corn yields from the USDA's National Agricultural Statistics Service (https://www.nass.usda.gov).

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°C is the best predictor of corn yields. Modern data indicate that high-yielding genetically modified varieties that are prevalent today are even more sensitive to extreme heat than the traditional varieties (Lobell, Schlenker, and Costa-Roberts 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 Roundup Ready corn) has made it easier to control weeds (Roundup, or glyphosate) and pests (through BT strains). Yet the large plants of today

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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 Meyers 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 et al. 2019).

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.

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 the progress and challenges of engineering improved photosynthesis through synthetic biology as a potential path toward improving the utilization of solar energy and carbon sources to produce food, fiber, and fuel.

I.4 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., Shih and Wright 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 institutions in creating and disseminating agricultural innovations (Wright 2012), establishing vital links among universities, farmers, and industry. With the 1862 act, the US 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 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 a 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 (1978), 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

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[3] Southern states 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.

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 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, 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 afterward, 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 Nelso, 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 toward identifying the causal effect of establishing a land grant college on invention, Andrews compares locations that received 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, 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 toward 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 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). Plant patent protection excludes plants that reproduce sexually, through seeds, as well as potatoes and other 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, nonpatent 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 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.

Investigating funding as a mechanism for encouraging innovation, Andrews shows that the effects of land grant colleges on local innovations were 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, land grant 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

4. Using new varieties of roses as a nonpatent 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 indicate 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.)

have diffused beyond the borders of the college county through a combination of outreach and university engagement (as described in chapter 5 of this book).

Placing Andrews'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 analysis of productivity spillovers, Alston et al. (2010) show that over half of the measured within-state productivity gains result from public research investments made elsewhere. Alston et al. 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 IRR of 22.7 for the entire nation. Thus the "failure" of the land grant system may lie in Alston et al.'s 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 N. 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 of Brian Wright's (2012) positive assessment of the land grant system. Citing the findings of Olmstead and Rhode (2002), Wright (2012, 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, 502), "Hybrid corn was the invention of a method of inventing." Citing primarily Stackman, Bradfield, and Mangelsdorf (1967), Wright (2012, 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).

I.5 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 science 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 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 start-ups).[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 I.3), which suggests that the institutional characteristics of universities play an important role in shaping links between academia and industry. 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 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 analyses 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.

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

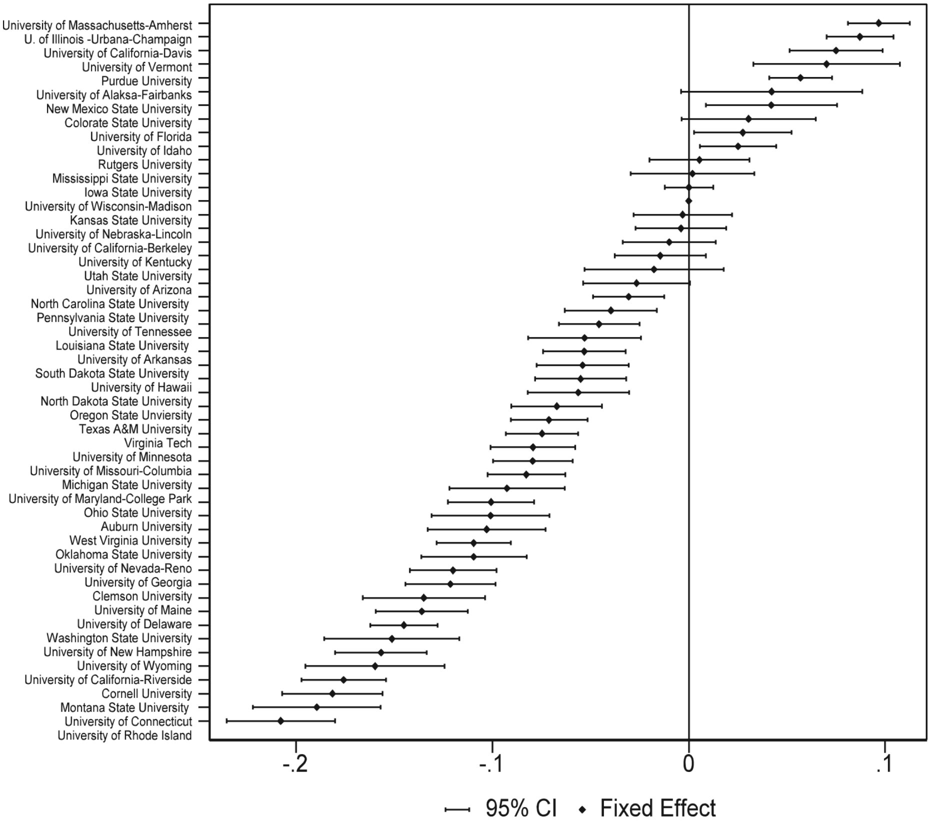

Fig. I.3 University-level probabilities of faculty engagement with industry

Note: From the chapter by Barham, Foltz, and Melo in this book (see chapter 5). OLS estimates and 95 percent confidence for 52 university fixed effects (with the University of Wisconsin-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 having received a PhD from a land grant university. Standard errors are clustered at the university level.

I.6 Financing Future Innovations through Venture Capital

A final chapter on “Venture Capital and the Transformation of Private R&D for Agriculture” 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 start-ups, especially in the wake of the financial crisis of 2008. Between the early 2000s and 2018, VC investments in start-ups focusing on agricultural R&D increased from just tens of millions to more than seven billion. Notably, VC investment in agriculture start-ups 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 sources (Crunchbase, PitchBook, and VentureSource) to construct a new data set consisting of 4,500 start-ups 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 and Beintema 2001; Pardey et al. 2006), the authors report robust start-up activities 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 start-ups across 124 countries. Although the largest share of the start-ups in their sample operates in the United States (33 percent) and the European Union (23 percent), a significant share of the remaining 44 percent of start-ups is in emerging economies. The authors' regressions indicate that investments are strongly correlated with past liquidity events, suggesting that the expansion of VC investment in agriculture start-ups reflects a response to new investment opportunities in agriculture.

For a subset of these start-ups, their data also include information on investment and exit deals between 1981 and 2018. These data indicate that successful exits, in the forms of initial public offerings (IPOs) and mergers and acquisitions (M&A), led to higher VC investments. 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 nonagricultural 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 start-ups 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 identities of investors, possibly by tracking the work histories of VC partners that choose to finance start-ups in agriculture. This question is particularly interesting and important because agriculture is a nontraditional investment for both VC and private equity.

I.7 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 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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