Discussion Paper No. 11-064

Industry-Science Connections in Agriculture: Do public Science Collaborations and Knowledge Flows Contribute to Firm-level Agricultural Research Productivity?

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Non-technical Summary

Academic institutions are an important component of the public agricultural research system in many countries. According to the "open science" model of research, these institutions produce new knowledge, methods, and materials that are disclosed and disseminated through channels such as journal publications to become part of the stock of public knowledge in agriculture. In turn, this stock of knowledge is expected to yield social returns by facilitating invention in the private and public sectors and ultimately improving agricultural productivity

Prior research finds that the stock of public knowledge in "pre-technology" science fields such as entomology contribute directly to long-run agricultural productivity in the U.S. These studies also show a direct effect of private sector patented inventions on agricultural productivity. However, the potential link between the stock of public knowledge and private invention is left unexplored. Private sector scientists may use public agricultural science to help overcome problems or to suggest completely new research projects. This would be an additional, but intermediate, channel connecting the public stock of knowledge to agricultural productivity. In the present study, we identify connections between the stock of public knowledge and private firms and examine whether the degree of "connectedness" to public science is associated with greater firm-level research productivity in agriculture.

Using a sample of US universities and large R&D performing public firms, connections between the stock of public knowledge and private R&D are identified using citations by firms to journal publications in agricultural science and public-private coauthored papers. This bibliographic information is combined with data on agricultural patenting and firm-level R&D investment to analyze how "connectedness" through either linkage influences research productivity using a panel of US companies covering the years 1986 to 1998.

The descriptive results show that annual scientific publications in US agriculture remained roughly unchanged for 1981-1999, in contrast to the relatively rapid growth in other life science fields. Moreover, agricultural science exhibits an uneven pattern of use by US private firms, with eleven "top" users accounting for 72% of all citations. The regression analysis, which focuses on firms in the chemical and allied products sector, shows that more connectedness to the stock of public knowledge in agriculture is associated with greater agricultural research productivity. On average, an additional citation to external agricultural science is associated with a 0.5% increase in agricultural patents while an additional co-authorship is associated with a 4.5% increase in agricultural patents.

Das Wichtigste in Kürze (Summary in German)

Akademische Institutionen sind eine wichtiger Bestandteil der öffentlichen Forschung im Bereich der Landwirtschaft. Gemäß des „open science“ Models, generieren diese Institutionen neues Wissen, Methoden und Materialien, die entdeckt und z.B. mithilfe von Journalpublikationen verbreitet und damit Teil des öffentlich verfügbaren Wissens werden. Im Gegenzug wird erwartet, dass das generierte Wissen der Gesellschaft nutzt, indem die Innovationsaktivität im privaten und öffentlichen Sektor stimuliert und schließlich die Produktivität in der Landwirtschaft erhöht wird.

Vorhergehende Studien finden, dass der Bestand öffentlichen Wissens in „prä-technologischen“ Forschungsfeldern wie z.B. der Entomologie direkt zur langfristigen Produktivitätssteigerung in den U.S. beitragen. Diese Studien zeigen ebenfalls einen direkten Effekt der patentierten Erfindungen des Privatsektors auf die Produktivität in der Landwirtschaft. Eine mögliche Beziehung zwischen dem Bestand öffentlichen Wissens und privaten Erfindungen wird jedoch nicht erforscht. Forscher im privaten Sektor könnten jedoch auf öffentliche Forschung im Bereich der Landwirtschaft zurückgreifen, um Probleme zu lösen oder völlig neue Forschungsprojekte vorzuschlagen. Dies wäre ein weiterer, wenn auch intermediärer, Weg wie der Bestand öffentlichen Wissens zur Produktivität in der Landwirtschaft beitragen könnte. In dieser Studie identifizieren wir Zusammenhänge zwischen dem Bestand öffentlichen Wissens und privaten Firmen und untersuchen, ob der Grad der „Vernetzung“ mit öffentlicher Forschung mit einer höheren firmenspezifischen Forschungsproduktivität in der Landwirtschaft einhergeht.

Auf Basis eines Datensatzes von U.S. Universitäten und großen öffentlichen Firmen, die Forschung und Entwicklung (FuE) treiben, werden Verbindungen zwischen dem Bestand öffentlichen Wissens und privater FuE identifiziert, indem Informationen über die Zitationen der Firmen von Journalpublikationen im Bereich der Landwirtschaft sowie öffentlich-private Mitverfasserschaften betrachtet werden. Diese bibliographische Information wird mit Daten über landwirtschaftliche Patente und firmenspezifische FuE Ausgaben kombiniert, um zu untersuchen wie die „Vernetzung“ über diese Verflechtungen die Forschungsproduktivität beeinflusst. Die Analyse basiert auf einem Paneldatensatz von Firmen in den U.S. zwischen 1986 und 1998.

Die deskriptiven Ergebnisse zeigen, dass die jährlichen wissenschaftlichen Publikationen im Bereich der Landwirtschaft in den US zwischen 1981 und 1999 ungefähr konstant blieben, wohingegen andere Forschungsbereiche stark wuchsen. Darüber hinaus zeigt sich ein uneinheitliches Nutzungsverhalten durch private Firmen in den US, mit 11 „top“ Nutzern, die insgesamt 72% aller Zitationen ausmachen. Die Regressionsanalyse, welche sich auf Firmen in der Chemiebranche konzentriert, zeigt, dass eine stärkere „Vernetzung“ zum Bestand öffentlichen Wissens in der Landwirtschaft mit einer höheren Forschungsproduktivität einhergeht. Im Durchschnitt führt eine zusätzliche Zitation zu externer landwirtschaftlicher Forschung zu einem Anstieg von landwirtschaftlichen Patenten um 0,5%, während eine zusätzliche Mitverfasserschaft mit einem Anstieg um 4,5% einhergeht.

Industry-Science Connections in Agriculture: Do public science collaborations and knowledge flows contribute to firm-level agricultural research productivity?[1]

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Abstract

Prior research shows long-run productivity growth in agriculture is associated with increases in the stock of public scientific knowledge and private patented inventions. However, private inventions may be a function of the stock of public knowledge. In this paper, we examine the possibility that public knowledge contributes to productivity through its relationship with private sector invention. Our analysis identifies connections between the stock of public knowledge and private firm R&D and examines whether the degree of "connectedness" to public science is associated with greater firm-level research productivity in agriculture. Bibliographic information identifies the nature and degree to which firms use public agricultural science through citations and collaborations on scientific papers. Fixed effects models show that greater citations and collaborations with university researchers are associated with greater private agricultural research productivity.

Keywords: public science, research productivity, patents, citations, collaboration, R&D, bibliometrics

JEL Classification: Q16, O31

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[1] The views expressed in this article are the authors' and do not necessarily represent the views of the U.S. Department of Agriculture or the Economic Research Service.

1. Introduction

Academic institutions are an important component of the public agricultural research system in the United States. Land grant universities, state agricultural experiment stations, and various other non-for-profit research institutions receive over seventy percent of public agricultural research and development (R&D) funds each year (Schimmelpfennig and Heisey 2009; Alston et al. 2010). According to the “open science” model of research, these funds are used to produce new knowledge, methods, and materials that are disclosed and disseminated through channels such as journal publications to become part of the stock of public knowledge in agriculture (Mukhergee and Stern 2009). In turn, this stock of knowledge is expected to yield social returns by facilitating invention in the private and public sectors and ultimately improving agricultural productivity.

This study identifies connections between the stock of public knowledge and private firms and examines whether the degree of “connectedness” to public science is associated with greater firm-level research productivity in agriculture. Studies by Huffman and Evenson (1993, 2006) find that the stock of public knowledge in “pre-technology” science fields such as entomology contribute directly to long-run agricultural productivity in the U.S. Their research also shows a direct effect of private sector patented inventions on agricultural productivity. However, the potential link between the stock of public knowledge and private invention is left unexplored. Private sector scientists may use public agricultural science to help overcome problems or to suggest completely new research projects (Cohen et al. 2002). This would be an additional, but intermediate, channel connecting the public stock of knowledge to agricultural productivity.

Connections between the stock of public knowledge and private firms are identified using bibliographic information contained in the firms’ scientific publications. The bibliographic data, which are from the NBER-Rensselaer scientific database, allow two different forms of industry-science links to be distinguished. First, citations by firms to publications in agricultural science fields are used to capture “arms-length” knowledge flows from universities and other firms. Second, public-private coauthored papers in agriculture measure firm collaborations with academic researchers, which is less “arms-length” and represents a more involved, interactive connection. The bibliographic information is combined with data on agricultural patenting and firm-level R&D investment to analyze how “connectedness” through either linkage influences research productivity using panel data covering the years 1986 to 1998.

In addition to this analysis, the paper presents descriptive results showing that annual scientific publications in agriculture remained roughly unchanged for 1981-1999, in contrast to the relatively rapid growth in other life science fields. Also, universities account for nearly all new publications adding to the stock of public knowledge in agriculture, although trends indicate that the share of publications by private firms grew faster. Moreover, agricultural science exhibits an uneven pattern of use by private firms, with eleven “top” users accounting for 72% of all citations. Even among these top users, scientific fields other than agriculture represent the focus of overall inventive and scientific output and input as measured by patents, publications, citations, and co-authorships. This reflects the importance of non-agricultural lines of business even to the firms with the greatest level of agricultural R&D.

The regression analysis in this study focuses on firms in the chemical and allied products sector (SIC 28). In the NBER-Rensselaer database, this sector contains 67% of the firms that cite agricultural science. Fixed effects regression models show that more connectedness to the stock of public knowledge in agriculture is associated with greater agricultural research productivity. The knowledge flow and collaboration indicators are positive and significant at the 1% level. On average, an additional citation to external agricultural science is associated with a 0.5% increase in agricultural patents (approximately 0.025 more patents per firm-year at the mean) while an additional co-authorship is associated with a 4.5% increase in agricultural patents (approximately 0.23 more patents per firm-year at the mean). These marginal benefits appear to stem from connectedness to universities and not private firms. There are relatively few citations and co-authorships between private firms and these are statistically insignificant in the regression models once connectedness to universities is held constant.

The rest of the paper is organized as follows. Section 2 outlines the conceptual framework used in our analysis and summarizes prior contributions. Section 3 presents the empirical model, discusses the estimation method, and describes the data and measures. Descriptive results based on the NBER-Rensselaer database and the regression results are reported in Section 4. Concluding comments appear in Section 5.

2. Background Literature

Figure 1 illustrates some of the complex relationships that connect contributions to the stock of public knowledge with changes in agricultural productivity. As represented by the bold arrow in the far right of the diagram, a substantial literature focuses on the direct relationship between public knowledge and productivity. Huffman and Evenson (2006) and Alston et al. (2010) summarize this literature and present new data and regression results for the United States. As these authors document, the direct effect of public agricultural knowledge is generally positive, statistically significant, and implies high rates of return to public investment. The bold arrow in the far upper left of the diagram – the one that links private agricultural invention to productivity – illustrates an indirect channel that passes through private research productivity. A handful of studies have considered this channel, but only partially (Huffman and Evenson 1993, 2006; Schimmelpfennig and Thirtle 1999).

Using patent data, these studies examine the link between agricultural multifactor productivity (MFP) and private agricultural invention measured using patents. With state-level data for 1970-1999, Huffman and Evenson (2006) find that a 1% increase in the stock of private patents increases state MFP by 0.1%. Based on country-level data for 1973-1993, Schimmelpfennig and Thirtle (1999) find positive and significant effects of domestic and foreign patent stocks on MFP, although the interaction term between the two stocks is negative. Their closed economy regression results matched those of Huffman and Evenson (2006) with an elasticity of MFP with respect to the stock of domestic patents of about 0.1.

As illustrated by the bold arrows in the far lower left of Figure 1, this paper considers the specific effect of the stock of public knowledge in agriculture on private sector invention. Our analysis of this potential link follows the conceptual model developed by Pakes and Griliches (1984) and discussed further in Griliches (1990). They introduced the "knowledge production function" model that has become the workhorse for empirical studies relating firm-level patents to R&D investment. In Figure 1, their model describes the bold arrows in the far lower left of the diagram – patents as a function of formal R&D investment and "informal" R&D inputs such as connectedness to the stock of public knowledge.[2]

In the literature, several studies have examined how firm-level research productivity or other measures of firm performance depend on connectedness to public knowledge. Among the possible channels that firms use to access public scientific knowledge,

[2] We view the invention process within a firm's knowledge production function as mostly applied research and development activities, although some fundamental or "basic" research may also be performed. The role of public knowledge is to add value to research leads that enhances the efficiency of applied research. Theoretical search models of the invention process elucidate this effect (Evenson and Kislev 1976; Nelson 1982; Gambardella 1992; Rausser and Small 2000).

collaboration through co-authorship and arms-length knowledge flows through citation have received the most attention.[3] Zucker et al. (1998, 2002) use counts of journal articles co-authored between firm scientists and university "star" scientists to capture tacit knowledge exchange through bench-level interactions. They argue that star scientists possess the most valuable intellectual human capital, especially in times of rapid change when new research methods emerge such as biotechnology's recombinant DNA technique. Knowledge is understood as mostly tacit and difficult to codify and communicate except through person-to-person contact. Focusing on firms using modern biotechnology methods, Zucker et al. (1998, 2002) regress various measures of company performance such as cumulative patents granted and total products in development on co-authorship counts and other covariates. Most of their regression models show that greater connectedness through co-authorships is significantly and positively related to firm performance.

Drawing on their qualitative research studying pharmaceutical innovation and management, Cockburn and Henderson (1998) suggested the broader concept of "connectedness" between a firm and the scientific community. Their concept emphasizes bidirectional information flows and active participation by firm scientists in the intellectual life of the broader scientific community through various channels such as professional meetings, joint publication, etc. that Cohen et al (2002) find most important. Concurring with Zucker and colleagues, Cockburn and Henderson also view co-authorship activity as a

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[3] Cohen et al. (2002) present survey evidence on the role and contribution of public science to industrial R&D collected from R&D managers in U.S. manufacturing firms. Public science contributes to new ideas for R&D projects, but it appears to be more important as a source of information for R&D project completion. In terms of how public knowledge is accessed, the top four mechanisms were publications and reports, meetings and conferences, informal interactions, and consulting.

particularly effective form of public-private interaction that facilitates tacit knowledge exchange. Citation activity by firm scientists, on the other hand, is characterized as impersonal and driven by arms-length learning, attribution, and other motives. Although Cockburn and Henderson (1998) did not empirically investigate the relative importance of co-authorships and citations, their arguments suggest the marginal contribution of co-authorships to firm research productivity is greater than that of citations.

In their quantitative work, Cockburn and Henderson (1998) examine the relationship between the number of important patents (defined as "triadic" patents which were granted in the U.S., Europe and Japan) and connectedness using "co-authorships" based on address information. For firm publications, they counted the number of different addresses listed in the Thomson-Reuters' Institute for Scientific Information (ISI) database and used this as a proxy for the number of co-authors. Their measure, which was defined as the fraction of university "co-authorships," has the advantage of not being restricted to star scientists, but relies on contact information rather than actual co-authorship occurrences. Using panel data on ten pharmaceutical firms observed in the 1980s, Cockburn and Henderson find a positive and significant relationship between connectedness and the number of important patents granted to the firm in most of their models. Only when firm fixed effects were added did the fraction of co-authorships with universities become insignificant. Overall, for the sample range of their measure, increasing the degree of connectedness from its lowest to its highest value led to an increase in research productivity of about 30 percent.

Two recent studies that incorporate both citation and co-authorship measures of connectedness find mixed results. Gittelman and Kogut (2003) use the stock of forward citations to a biotechnology firm's patents as an indicator of successful innovation.[4] They

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[4] "Forward citations" of a given patent refer to future patents that eventually cite it. "Backward citations" refer

find that the "science intensity" of a firm, measured by a count of backward patent citations to non-patented literature, increases performance. However, holding science intensity constant, the percentage of co-authorships with external organizations is only marginally significant and becomes insignificant when fixed effects are added to the model. For a sample of biotechnology and pharmaceutical firms, Fabrizio (2009) defines the average annual flow of forward citations to a firm's patents as the performance indicator. Her empirical model, which is specified at the level of patent technology classes within firms over time, incorporates citations and co-authorships at different levels of aggregation. At the technology class-firm-year level, average backward patent citations to patent prior art are found to significantly increase firm performance. However, holding citations constant, the percentage of annual publications co-authored with university scientists measured at the firm-year level is never significant.

3. Empirical Model, Data, and Measurement

Our empirical model follows the knowledge production function approach introduced by Pakes and Griliches (1984) and used by others in the literature such as Cockburn and Henderson (1998). As described in Section 4, the majority of firms using the stock of public knowledge in agriculture are part of the chemical and allied products sector (SIC 28). The regression analysis focuses on firms in this sector, which includes suppliers of agricultural inputs including pesticides, seed, veterinary pharmaceuticals, as well as firms in the nascent field of agricultural biotechnology. Although our industry focus does not capture firms in farm machinery, fertilizer, or other areas related to agriculture, restricting our analysis to a single industry minimizes inter-industry differences in the propensity to patent and allows

to patents in the past that it cites.

comparison with other SIC 28 life-science firms. We estimate a firm-level model of the following form:

(1) $$\ln\left(Agpats\right)_{it} = \beta_0 + \beta_1 \ln\left(R\,\&\,D\right)_{i,t-1} + \mathbf{Connect_{i,t\text{-}1}}\boldsymbol{\delta} + \mathbf{Z}_{\mathbf{i,t}-1}\boldsymbol{\gamma} + \mu_i + \tau_t + \varepsilon_{it}$$

where $\ln(Agpats)_{it}$ is the natural logarithm of agricultural patents (dated by year of application) for firm *i* in year *t*; $\ln(R\&D)_{i,t-1}$ is the natural log of real research and development expenditure by firm *i* lagged one year; $\boldsymbol{Connect_{i,t-1}}$ is a group of indicators of connectedness to the stock of public knowledge at firm *i* in year (*t*-1) through knowledge flows or collaboration. As discussed in Section 2, the empirical analysis examines citations and co-authorships as indicators of these alternative forms of connectedness. $\mathbf{Z}_{\boldsymbol{i,t-1}}$ is a group of control variables for firm *i* in year (*t*-1); μ_i are firm fixed effects; τ_t are yearly dummy variables, and ε_{it} is an idiosyncratic error term.

Our database is an unbalanced firm-year panel with thirty four firms observed from 1986 through 1998. We assume firm-year observations are missing at random. The models are implemented using a linear fixed effects estimator. The fixed effects estimator also imposes "strict exogeneity" on the explanatory variables so that shocks to agricultural patents at time t are not allowed to influence future (*t*+1 and beyond) values of the explanatory variables. Following Wooldridge (2002), we tested for the failure of the strict exogeneity assumption by including the lead of the firm's R&D investment, $\ln(\text{R\&D})_{i,t+1}$. This test found no evidence that our models violate the strict exogeneity assumption. All of the explanatory variables are lagged and can be considered pre-determined in the regression models.[5] It is important to keep in mind that the reduced form models we estimate do not

[5] We also explored specifications that allowed for up to five years of lagged private R&D in an attempt to characterize some of the dynamics within the firms' innovative processes. Consistent with the literature, the

permit strong causal inference.

Data and Measurement

This paper draws on three major databases. The NBER-Rensselaer database, developed by Adams and Clemmons (2008) and available online from the National Bureau of Economic Research (NBER), provides publication, citation, and co-authorship information from scientific papers. It was created from the Thomson-Reuters' Institute for Scientific Information (ISI) database on journal publications covering the 1981-1999 time period. The database includes more than 2.5 million publications with over 21 million associated citations for 110 U.S. research universities and 198 public U.S.-based R&D performing firms. (Adams and Clemmons (2008) provide complete documentation.) The NBER-Rensselaer bibliometric data were supplemented with information on firm-level R&D investment and employment data from Compustat. Using the firms' CUSIP numbers, ninety-five percent (or 189 firms) of the 198 NBER-Rensselaer firms successfully matched Compustat with at least one year of financial data. The NBER patent database provided firm-level counts of patents granted by application date. The probability that firm patents had an agricultural application rather than another field of use was determined using the OECD Technology Concordance (OTC) system developed by Daniel K.N. Johnson (2002). The OTC system estimates the probabilities for different intended sectors of use of a given patent based on its International Patent Classification and has been used extensively in the literature to study agricultural patenting (e.g. Huffman and Evenson 2006). Summary statistics for all variables used in the

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first lag of R&D was the largest and most significant. High collinearity produced low precision and alternating signs on the other coefficients (see Hall et al. 1986; Pardy 1989; Adams 1990; Cincera 1997; Toole 2007, 2011). The magnitude and significance of the connectedness indicators were nearly identical to those presented in Tables 5 and 6 in Section 4.

regression analysis are reported in Table 1.

Citation and co-authorship information from the firms' annual publications is used to construct indicators of knowledge flows that represent connectedness to the stock of public knowledge. Counts of backward citations (that is, citations to previously published work) capture the degree to which firms draw on external science using arms-length relationships. Three types of citations are identified. Citations to the firms' own prior research, called "internal citations," provide an index of "inwardness" or reliance on in-house research capabilities. External citations to publications in agricultural science fields, called "Ag external citations," indicate the degree to which firms use agricultural public science. External citations to publications in all other fields of science, called "non-Ag external citations," capture the use of non-agricultural science. In the NBER-Rensselaer database, instances of co-authorship are always external to the firm. The number of co-authorships in agricultural science fields, called "Ag external co-authorships," indicates the degree to which firms interact and collaborate with university and private firm agricultural scientists. A similar definition applies to "non-Ag external co-authorships."

Besides annual real research and development (R&D) investment, which holds firm-level inputs into invention constant, two other control variables are used in the regression analysis. Annual total employment is used in some models to hold invention constant with respect to firm size. Following Cockburn and Henderson (1998), real R&D expenditures per publication control for firm "science intensity," which is related to its internal capabilities and "absorptive capacity" to make use of externally performed research (Cohen and Levinthal 1989).

4. Descriptive and Regression Results

4.1 Public Agricultural Science and its Usage by Private Firms

The first part of this section presents new information on the evolution of public knowledge in agriculture using the publication activity of universities and firms from 1981 to 1999. As mentioned in the introduction, the disclosure and dissemination of research findings is a hallmark of open science and journal publications are the primary mechanism for adding to the stock of public knowledge. The second part of this section looks at the firms using public knowledge in agriculture and classifies these firms based on their citation activity.

Figure 2 reports the levels and trends in publication activity for the life science components of agriculture, biology, and medicine based on the field designations defined by the National Science Foundation (NSF). Relative to biology and medicine, knowledge flows into public agricultural science are small. In 1981, agricultural science publications totaled about 9,200 which is less than one-third the volume observed in biology and medicine. Over the next eighteen years, the flow of agricultural science publications remained mostly unchanged, with an average annual growth rate of 0.3% while publications in medicine and biology grew by 2.7% and 2.8% per year, respectively.[6]

Focusing on agriculture, Figure 3 shows the breakout and trend in agricultural science publications by universities (right vertical axis) and private firms (left vertical axis). Both

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[6] Note that publications relative to share of GDP diverged in the opposite direction. While agricultural publications grew at a rate of -0.3% annually, Bureau of Economic Analysis estimates average annual growth in private agricultural value-added GDP at -1.6% during this period. Pharmaceutical and other biological publications grew at 1.3% while health care and social assistance value-added GDP grew at an average annual rate of 5.1%.

sources show a slight upward trend with universities contributing 97% of all publications to the stock of public knowledge in agriculture. This is not unusual. The NBER-Rensselaer data shows the median contribution of universities to open science is 96% across all NSF fields and years. However, in agriculture the relative contribution of private firms is increasing over time, which corresponds to a period over which private sector R&D eclipsed public funding (USDA Economic Research Service, 2010). Over the whole period university publications grew at an average annual rate of 0.3% while private firm publications grew at 1.3%.

Within agricultural science, the NBER-Rensselaer database identifies nine sub-fields. Table 2 reports the average number of publications and growth rates for universities and firms within each of these fields. The heterogeneity across sub-fields is apparent.[7] For both universities and firms the sub-fields of plant science and veterinary/animal health have the largest volume of publications. Setting the "animal and plant science" sub-field aside due to potential measurement error, the publication growth rates for universities are negative in the majority of the sub-fields. It is unclear whether this reflects public funding for agricultural research, changes in scientific research opportunities, or other explanations. On the other hand, the growth rates for firm publications are mostly positive, especially in entomology/pest control and aquatic sciences. These trends may reflect changes in public support for agricultural science and/or a possible shift away from scientific toward commercial research opportunities affecting the locus of public versus private research in agriculture. It will be important in future research to examine the nexus between public funding and research opportunities in agricultural sciences to better understand the

[7] The data for "animal and plant science" is small and many years have missing information. This may reflect limitations in the journal classification process used for the NBER-Rensselaer database.

implications of these trends for stock of public scientific knowledge and agricultural productivity more generally.

To be effective at stimulating greater agricultural yields and other productivity benefits through the indirect channel, the knowledge base provided by published agricultural research should be used by firms and other agents to discover and develop new products and processes. From the NBER-Rensselaer database, we identified firms that use agricultural science based on citations to past scientific research published by universities and other firms. Conditional on citing agricultural science at least once, firms in the 90th percentile of the distribution of total citations to were designated as “top users”. Eleven firms of the 198 NBER-Rensselaer firms with 396 or more total citations in the sample period make up this group. Firms were designated as “other users” if they had nineteen or more citations to external agricultural science.[8] Forty-one firms compose this group. The remaining NBER-Rensselaer firms were classified as non-agricultural science users.

Table 3 presents a profile of the eleven top Ag-using firms over two time periods: 1986-1991 and 1992-1998.[9] Panels A & B report the average values of several output and input indicators for these time periods. All of the top Ag-users except Nabisco are in the chemical and allied products sector, an artifact of the historical emergence of large chemical companies from the artificial fertilizer and pharmaceutical industries (SIC 2834). It is also clear that agriculturally related patent applications, publications, citations, and co-authorships

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[8] The lower bound of nineteen total citations was picked based on inspection of the data. There were several firms that published a few papers with citations, but these firms were not systematic users of agricultural science.

9 Analysis of the backward citation data showed a clear truncation bias prior to 1986. We dropped 1999 to avoid problems with merger activity.

represent a relatively small share of the overall invention and science activities of these firms except Nabisco. DuPont, Nabisco, and Proctor & Gamble (P&G) averaged the highest number of Ag-related patents in 1986-1991, but Monsanto overtook DuPont and Nabisco in the period from 1992 to 1998 to share the top with P&G. In both periods, Monsanto was the leader in external citations to public agricultural science and in Ag co-authorships. As indicated by the number of Ag self-citations, Merck and Monsanto utilized their own internal agricultural capabilities for research more than other top Ag-users.

To assess changes over time, Panel C shows growth rates between the first and second period values reported in Panels A & B. Agricultural patents and publications grew faster than non-agricultural patents and publications at Monsanto, Pharmacia/UpJohn, and Merck with Monsanto showing the most dramatic differences. Monsanto, DuPont, Pharmacia/UpJohn, P&G, and Nabisco show greater growth in self citations to agricultural science fields than to non-agricultural science fields. This suggests a building up or reliance on internal agricultural science capabilities. For external science usage, Monsanto, DuPont, and Pharmacia/UpJohn show greater growth in non-self citations to Ag science fields than to non-Ag science fields. These firms also show greater growth in co-authorships in Ag relative to non-Ag. Dow Chemical stands out for its negative growth rates in Ag patents, Ag papers, and self-citation to agriculture. For the sample period covered by these data, Dow Chemical appears to be moving away from its agricultural focus, although the NBER-Rensselaer data does not reflect Dow's purchase Mycogen in 1997. King and Schimmelpfennig (2005) note that Dow had the greatest share of agricultural biotechnology patents acquired through mergers and acquisitions among major agricultural biotechnology firms.

Table 4 contrasts the group of top Ag-using firms with the categories of "other" users and non-agricultural science using firms. From Panel A, it is clear that all three groups have similar average R&D intensities (real R&D/real sales). Nevertheless, the publication and citation data suggest the groups of top and other Ag-using firms are more science intensive than non-Ag using firms. For instance, indicators such as total papers, total citations per paper, self and non-self cites to non-agricultural science all decrease when moving from the group of top Ag-users to non-Ag users. (Indicators related to agricultural papers, citations, and coauthorships will decrease by construction.) This is part of the motivation for including R&D per publication as a control variable in the regression analysis. The number co-authorships per paper, on the other hand, increase slightly when comparing top Ag-users to non-Ag using firms. Because the top Ag-using firms are concentrated in the chemical and allied products sector, Panel B shows the breakout for this sector. In Panel B, the R&D intensities are much higher for the other user and non-Ag user groups, but the same general pattern of science intensity emerges.

4.2 Regression Results

Table 5 presents the first regression results examining the relationship between private agricultural research productivity and connectedness to the stock of public knowledge. Each of the regression models account for firm-level fixed effects and report the Newey-West heteroskedasticity and serial correlation robust standard errors. All explanatory variables are lagged one period to minimize potential simultaneity. In this table, the degree of connectedness between a firm and external science is measured using the backward citations contained in the firms' annual publications. Model (1) shows that the number of agricultural patents, which are dated by the year of application, is positively related to firm R&D investment. The elasticity indicates that a 10% increase in R&D investment is associated with a 5% increase in agricultural patent applications in the following year.

To capture knowledge flows through arms-length relationships, model (2) includes counts of backward citations to the science literature for agricultural and non-agricultural fields. The number of self-citations is also included to avoid confounding in-house research capabilities with the use of external knowledge. The number of citations to agricultural sciences is positively related to research productivity and is significant at the 5% level. On average, one additional citation to external agricultural science is associated with a 0.5% in agricultural patent applications in the following year. With firm-level R&D investment already in the model, self-citations do not make any additional contribution to research productivity. Also, the number of citations to all other non-agricultural science fields is not significant.

Models (3)-(5) add additional control variables to investigate the robustness of the effect of connectedness on agricultural research productivity and assess the relative contribution of university versus private firm public science. Model (3) holds constant the overall scientific productivity of the firm as measured by total papers published per R&D dollar which captures the firm's investment in basic science and absorptive capacity. As was found by Fabrizio (2009), it is positive and significant at the 5% level. Model (4) controls for firm size by including the log of total firm employees. Firm size is not significant in any of the regression models and does not affect the magnitude or standard errors of the other coefficient estimates. This might reflect the scale of non-agricultural activities in the large sample firms. In model (5), external citations in agricultural science fields made to universities and private firms are entered separately in the specification. The effect is completely driven by citations made to universities, which is not surprising in light of the very small number of firm-to-firm citations observed in the data. Across all models, the magnitude and statistical significance of external citations to the stock of public knowledge in agriculture is robust. Firm-level agricultural research productivity is positively related to connectedness to public agricultural science, but not with connectedness to other non-ag science fields.[10]

Table 6 shows the regression results using publication co-authorships as an alternative mode of connectedness. Both citations and co-authorships cannot be used in the same model due to collinearity. For instance, the correlation between Ag external citations and Ag external co-authorships is 0.85 (0.92 for the Non-Ag variables) and significant at the 1% level. Model (1), along with R&D investment, includes the number of external co-authorships in agricultural and non-agricultural science fields lagged one year. Similar to the results using citations, only the number of co-authorships in agricultural science fields is positive and significantly related to agricultural patenting. On average, each additional external co-authorship is associated with a 4.3% increase in agricultural patents. Model (2) holds constant the firms' papers per R&D dollar to account for its absorptive capacity. Absorptive capacity is positively associated with agricultural patenting and is significant at a 5% level. Model (3) adds firm size to the specification. It is insignificant. Model (5) breaks out Ag co-authorships between universities and other private firms. Once again, universities drive the results. In all of the models, the number of co-authorships in non-agricultural science does not show a significant contribution to firm-level patents related to agriculture.

5. Conclusion

This paper described the breadth and frequency of connections between U.S. R&D

[10] It may be the case that firms have different propensities to cite the literature in their publications. The productivity effect of citations to public knowledge in agriculture might reflect changes in the propensity to cite within the firm over time. In unreported regression models, we include citations per paper to control for this possibility. The firms' number of citations per paper is not significant and does not affect the size of significance of Ag external citations.

performing firms and university performed public science in agricultural and explored whether the degree of connectedness is associated with greater firm-level research productivity. It is the first analysis to use firm-level data on citations and co-authorships in agricultural science publications to expose public-private collaboration and knowledge flows. In the sample of 189 large R&D performing firms, fifty-one have connections to agricultural public science with eleven "top user" firms accounting for 72% of the agricultural citations in the fourteen year sample period. For the allied and chemical products sector, which contains 67% of all the firms citing agricultural university science, the regression models indicate that both citation and co-authorship connections stimulate private agricultural patenting. Although prior studies such as Zucker and Darby (1998) and Cockburn and Henderson (1998) only analyzed co-authorships, our finding that citations have a smaller marginal effect on research productivity than co-authorships is consistent with their arguments favoring an interactive exchange of knowledge between public and private researchers. However, co-authorship is also more costly than arms-length citations and understanding the proper balance between these forms of connectedness will require further research that extends this analysis to incorporate firm-level costs.

The findings do not support an insular conception of how large R&D firms develop agricultural inventions. Holding other research inputs constant, connectedness to public agricultural science increases firm patenting and this implies that agricultural public science is contributing to agricultural productivity growth through its effect on private invention. To date the literature estimating rates of return to public agricultural R&D investment ignore this channel; however, given the magnitude and growth in private agricultural R&D, this channel is likely to become more important over time.

While the bibiometric data analyzed provide new information and insight into the relationship between public agricultural research and private firm invention, there are a number of limitations that remain to be addressed in future research. For instance, it will be important to collect richer bibliometric data that include small and medium size privately-held agribusiness in order to have a better understanding of how connectedness varies in the overall population of firms. The mechanisms private firms use to access public research have been studied by Cohen et al. (2002), but little is known about the nature agricultural innovation by private firms or how it diffuses to farm and non-farm agribusiness. In this regard, more research is needed to identify and analyze agricultural patenting and other forms of innovation.

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Table 1: Descriptive Statistics (410 firm-year observations, 1986-1998)

Variable	Mean	Standard Deviation	Minimum	Maximum
Ag Patent Apps (t)	5.06	6.26	0.023	44.58
Real R&D(t-1) [millions $]	414.35	433.34	1.76	2385.51
Employment (t-1) [1000s]	28.81	29.54	0.11	146.02
Total Ag External Citations(t-1)	21.46	40.04	0	305
Ag External Citations to Universities(t-1)	19.82	37.46	0	289
Ag External Citations to Private Firms(t-1)	1.64	3.36	0	24
Non-Ag External Citations(t-1)	1481.22	1952.26	0	10105
Internal Citations(t-1)	340.36	485.31	0	2949
Total Ag External Coauthorships(t-1)	2.00	3.69	0	28
Ag External Co-authorships with Universities(t-1)	1.86	3.52	0	27
Ag External Co-authorships with Private Firms(t-1)	0.13	0.44	0	3
Non-Ag External Coauthorships(t-1)	56.88	61.89	0	305
Papers per R&D dollar(t-1)	0.65	1.38	0.01	14.80

All variables are in levels. Data is an unbalanced panel of 34 firms with an average of 12.1 years per firm.

Table 2: Contributions to Agricultural "Open Science" by Field: 1981-1999

Ag Science Field	Average University Papers	Average Firm Papers	Average Growth Rate: University papers	Average Growth Rate: Firm papers
Plant Science	3028	59	-0.2%	1.9%
Veterinary/Animal Hlth	1847	80	0.4%	0.6%
Animal Science	1531	22	-0.1%	-1.6%
Agriculture/Agronomy	1259	53	-1.5%	-2.6%
Entomology/Pest control	1078	21	-0.8%	3.5%
Aquatic Science	839	9	2.2%	3.4%
Food Science/Nutrition	794	37	-0.3%	1.7%
Agricultural Chemistry	98	17	6.6%	7.7%
Animal & Plant Science	3	3	12.8%	13.9%

Table 3: Top Firms Using Agricultural Public Science

Panel A: Average Values, 1986-1991

FIRM NAME	SIC	R&D Intensity	All Patents	Ag Patents	Total Pubs.	Ag Pubs.	Total Cites per Pub.	Self Cite Ag	Non-self Cite Ag	Self Cite Non-Ag	Non-self Cite Non-Ag	Ag Coauthorships	Non-Ag Coauthorships	External Cites per Pub.	Coauthorships per Pub.
MONSANTO CO	2800	0.07	85	7	201	27	8	33	110	235	1264	10	58	6.8	0.33
DU PONT (E I) DE NEMOURS	2820	0.04	490	16	550	22	8	31	78	1002	3497	4	170	6.4	0.31
PHARMACIA & UPJOHN INC	2834	0.14	28	2	420	16	8	16	59	655	2820	6	111	6.7	0.28
LILLY (ELI) & CO	2834	0.13	77	4	267	18	8	11	42	480	1713	6	80	6.3	0.32
MERCK & CO	2834	0.11	172	8	530	26	10	40	43	1241	3964	5	122	7.4	0.24
DOW CHEMICAL	2821	0.05	355	13	159	9	4	6	31	147	501	3	34	3.3	0.23
BRISTOL MYERS SQUIBB	2834	0.07	117	5	244	22	8	13	29	274	1677	1	73	6.4	0.30
PROCTER & GAMBLE CO	2840	0.03	140	23	118	9	6	4	23	128	522	4	33	4.5	0.31
SCHERING-PLOUGH	2834	0.10	30	1	290	11	11	5	21	785	2364	2	80	8.0	0.28
PFIZER INC	2834	0.09	78	4	162	14	6	20	18	172	812	4	34	4.9	0.23
NABISCO GROUP HLDGS CORP	2052	-	33	24	25	5	7	1	28	25	113	1	5	5.6	0.23

Panel B: Average Values, 1992-1998

FIRM NAME	SIC	R&D Intensity	All Patents	Ag Patents	Total Pubs.	Ag Pubs.	Total Cites per Pub.	Self Cite Ag	Non-self Cite Ag	Self Cite Non-Ag	Non-self Cite Non-Ag	Ag Coauthorships	Non-Ag Coauthorships	External Cites per Pub.	Coauthorships per Pub.
MONSANTO CO	2800	0.09	99	16	182	36	13	65	200	291	1754	17	63	10.9	0.45
DU PONT (E I) DE NEMOURS	2820	0.04	364	12	438	23	10	38	128	871	3323	7	183	7.9	0.44
PHARMACIA & UPJOHN INC	2834	0.17	64	4	499	22	14	35	143	1134	5503	13	143	11.3	0.31
LILLY (ELI) & CO	2834	0.16	193	10	440	21	13	23	66	1017	4736	8	166	10.8	0.40
MERCK & CO	2834	0.09	221	12	817	41	14	69	92	2475	8894	8	246	10.9	0.31
DOW CHEMICAL	2821	0.05	191	4	179	7	7	3	43	244	979	3	62	5.8	0.37
BRISTOL MYERS SQUIBB	2834	0.09	96	5	510	8	18	5	27	1376	7637	2	229	15.1	0.46
PROCTER & GAMBLE CO	2840	0.04	376	30	193	9	11	15	52	329	1760	3	102	9.2	0.55
SCHERING-PLOUGH	2834	0.13	47	2	471	16	17	8	46	1691	6073	5	124	13.0	0.27
PFIZER INC	2834	0.14	101	6	328	29	12	39	71	459	3353	6	126	10.1	0.40
NABISCO GROUP HLDGS CORP	2052	0.01	9	8	36	10	10	16	31	59	209	2	10	7.6	0.35

Panel C: Growth Rates from Panel A to Panel B

FIRM NAME	SIC	R&D Intensity	All Patents	Ag Patents	Total Pubs.	Ag Pubs.	Total Cites per Pub.	Self Cite Ag	Non-self Cite Ag	Self Cite Non-Ag	Non-self Cite Non-Ag	Ag Coauthorships	Non-Ag Coauthorships	External Cites per Pub.	Coauthorships per Pub.
MONSANTO CO	2800	28%	15%	75%	-10%	28%	46%	68%	60%	21%	33%	60%	9%	47%	29%
DU PONT (E I) DE NEMOURS	2820	-5%	-30%	-25%	-23%	7%	19%	20%	50%	-14%	-5%	64%	7%	21%	33%
PHARMACIA & UPJOHN INC	2834	19%	81%	89%	17%	32%	51%	79%	89%	55%	67%	76%	26%	53%	12%
LILLY (ELI) & CO	2834	20%	92%	96%	50%	14%	47%	72%	44%	75%	102%	23%	73%	53%	21%
MERCK & CO	2834	-21%	25%	42%	43%	46%	36%	54%	76%	69%	81%	56%	70%	39%	27%
DOW CHEMICAL	2821	2%	-62%	-108%	12%	-31%	52%	-80%	34%	51%	67%	13%	60%	56%	48%
BRISTOL MYERS SQUIBB	2834	20%	-19%	4%	74%	-107%	86%	-107%	-5%	161%	152%	123%	114%	86%	43%
PROCTER & GAMBLE CO	2840	13%	99%	28%	49%	5%	68%	129%	81%	94%	122%	-30%	113%	73%	58%
SCHERING-PLOUGH	2834	23%	45%	52%	48%	36%	44%	54%	79%	77%	94%	83%	44%	48%	-3%
PFIZER INC	2834	45%	25%	29%	71%	71%	64%	70%	138%	98%	142%	33%	131%	72%	57%
NABISCO GROUP HLDGS CORP	2052	-	-130%	-110%	36%	78%	39%	294%	11%	86%	61%	107%	66%	30%	43%

Table 4: Firm-level Agricultural Science Use by Private Firms

Panel A: Firm-year Average Values (all available data)

GROUP	Years	R&D Intensity	All Patents	Ag Patents	Total Pubs.	Ag Pubs.	Total Cites per Pub.	Self Cite Ag	Non-self Cite Ag	Self Cite Non-Ag	Non-self Cite Non-Ag	Ag Coauthorships	Non-Ag Coauthorships	External Cites per Pub.	Coauthorships per Pup.
Top Ag (11 firms)	1986-1990	0.08	146	10	256	16	7.1	15	38	429	1563	4	66	5.7	0.3
	1991-1994	0.10	153	9	359	18	11.0	24	72	812	3301	6	120	8.9	0.4
	1995-1998	0.09	178	11	363	22	13.2	31	85	911	4238	7	138	10.9	0.4
Other Ag (41 firms)	1986-1990	0.10	97	2	152	2	5.8	1	4	330	706	0	48	4.7	0.4
	1991-1994	0.11	132	2	177	2	7.5	1	5	413	1165	1	73	6.2	0.4
	1995-1998	0.08	185	3	149	2	9.4	1	9	309	1398	1	74	8.1	0.5
Non-Ag (137 firms)	1986-1990	0.10	81	1	27	0	3.1	0	0	24	83	0	12	2.6	0.4
	1991-1994	0.10	91	1	24	0	4.1	0	0	19	98	0	13	3.7	0.5
	1995-1998	0.11	156	1	32	0	5.1	0	0	23	174	0	20	4.7	0.6

Panel B: Firm-year Average Values for Chemical and Allied Products Sector

GROUP	Years	R&D Intensity	All Patents	Ag Patents	Total Pubs.	Ag Pubs.	Total Cites per Pub.	Self Cite Ag	Non-self Cite Ag	Self Cite Non-Ag	Non-self Cite Non-Ag	Ag Coauthorships	Non-Ag Coauthorships	External Cites per Pub.	Coauthorships per Pup.
Top Ag (10 firms)	1986-1990	0.08	156	8	279	17	7.1	16	39	470	1709	4	73	5.7	0.27
	1991-1994	0.10	167	9	393	19	11.0	25	76	890	3615	7	131	8.9	0.37
	1995-1998	0.10	192	12	399	23	13.2	34	92	1004	4682	7	152	11.4	0.42
Other Ag (15 firms)	1986-1990	0.20	52	4	85	3	8.3	1.2	5	171	675	1	31	6.8	0.38
	1991-1994	0.23	68	4	124	3	11.1	1.3	8	285	1427	1	59	9.3	0.46
	1995-1998	0.15	77	4	154	3	13.5	1.2	14	369	2279	1	79	11.7	0.50
Non-Ag (10 firms)	1986-1990	0.29	34	2	15	0	6.3	0	0	19	115	0	8	5.4	0.49
	1991-1994	0.22	31	2	21	0	8.6	0	0	25	178	0	10	7.6	0.47
	1995-1998	0.16	35	1	25	0	10.6	0	0	38	268	0	12	9.4	0.45

Table 5: Science Citation and Private Agricultural Research Productivity (1986-1998): Firm-level Fixed Effects

	(1)	(2)	(3)	(4)	(5)
Dependent Variable:	Ag Patent Apps	Ag Patent Apps	Ag Patent Apps	Ag Patent Apps	Ag Patent Apps
Ag External Citations(t-1)		0.005 (0.0015)***	0.005 (0.0015)***	0.005 (0.0015)***	
Ag External University(t-1)					0.005 (0.0019)***
Ag External Private Firm(t-1)					0.001 (0.0105)
Non-Ag External Citations(t-1)		0.0001 (0.0001)	0.0001 (0.0001)	0.0001 (0.0001)	0.0001 (0.0001)
Internal Citations(t-1)		-0.0002 (0.0003)	-0.0001 (0.0003)	-0.0001 (0.0003)	-0.0001 (0.0003)
ln R&D (t-1)	0.510 (0.086)***	0.491 (0.082)***	0.634 (0.110)***	0.663 (0.153)***	0.661 (0.153)***
Papers per R&D Dollar(t-1)			0.075 (0.038)**	0.077 (0.039)**	0.077 (0.039)**
ln Emp(t-1)				-0.035 (0.133)	-0.034 (0.133)
Year Dummy Variables	Y	Y	Y	Y	Y
R-squared	0.1991	0.2270	0.2319	0.2322	0.2323
Root MSE	0.6727	0.6609	0.6577	0.6587	0.6586
Observations	410	410	410	410	410

*** indicates significance at a 1% level (**, *) for 5% and 10% levels for two-sided tests.

Newey-West H/SC standard errors in parentheses (Bartlett weights, bandwidth=3).

Fixed effects regressions were performed using the "xtivreg2" STATA command developed by Schaffer(2010).

Table 6: Science Co-authorships and Private Agricultural Research Productivity (1986-1998): Firm-level Fixed Effects

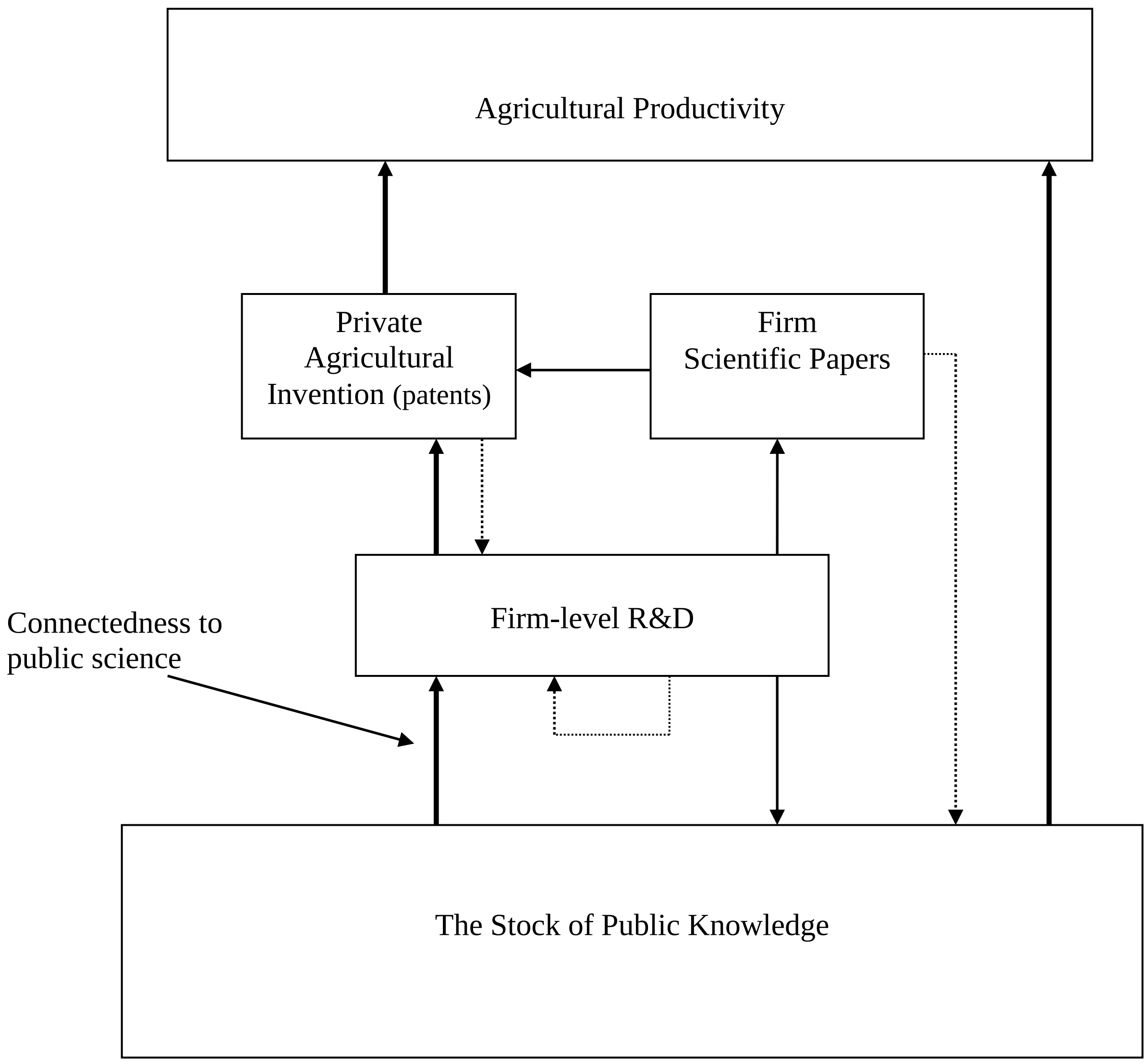
	(1)	(2)	(3)	(4)
Dependent Variable:	Ag Patent Apps	Ag Patent Apps	Ag Patent Apps	Ag Patent Apps
Ag External Co-authorships(t-1)	0.043	0.043	0.043	
	(0.012)***	(0.012)***	(0.012)***	
Ag External University(t-1)				0.045
				(0.013)***
Ag External Private Firm(t-1)				0.007
				(0.066)
Non-Ag External Co-authorships(t-1)	0.001	0.0005	0.0005	0.0005
	(0.001)	(0.0014)	(0.0014)	(0.0014)
ln R&D (t-1)	0.505	0.659	0.706	0.703
	(0.080)***	(0.102)***	(0.142)***	(0.142)***
Papers per R&D Dollar(t-1)		0.086	0.089	0.089
		(0.036)**	(0.036)**	(0.036)**
ln Emp(t-1)			-0.059	-0.059
			(0.136)	(0.136)
Year Dummy Variables	Y	Y	Y	Y
R-squared	0.2200	0.2270	0.2273	0.2277
Root MSE	0.6639	0.6609	0.6608	0.6606
Observations	410	410	410	410

*** indicates significance at a 1% level (**, *) for 5% and 10% levels for two-sided tests.

Newey-West H/SC standard errors in parentheses (Bartlett weights, bandwidth=3).

Fixed effects regressions were performed using the "xtivreg2" STATA command developed by Schaffer(2010).

Figure 1: Simplified path analysis diagram of agricultural productivity



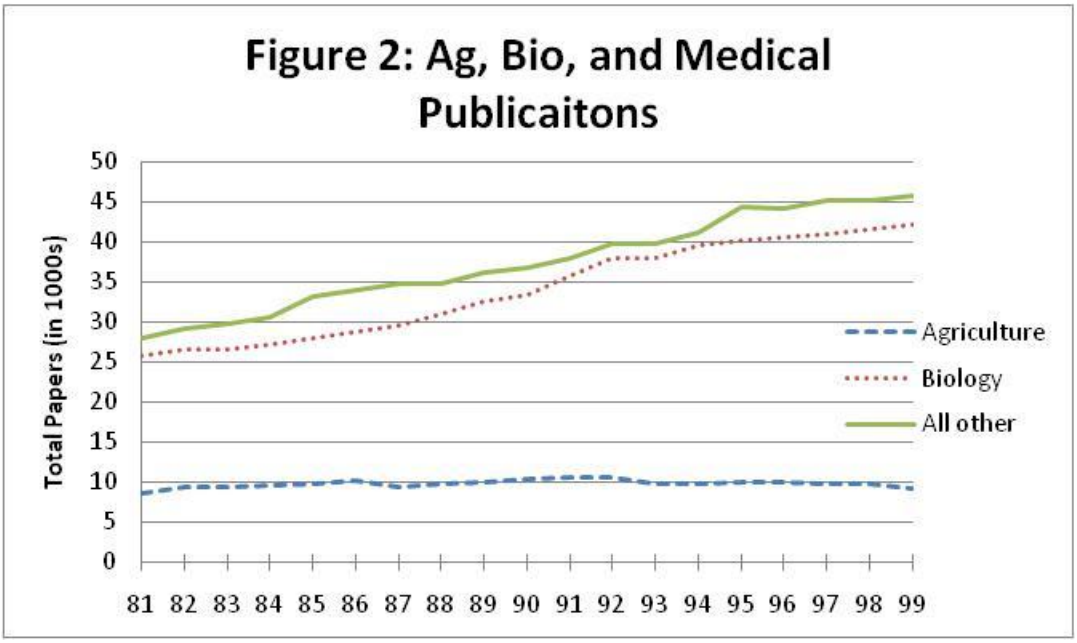


Figure 2: Ag, Bio, and Medical Publicaitons
Total Papers (in 1000s)
50
45
40
35
30
25
20
15
10
5
0
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99
Agriculture
Biology
All other

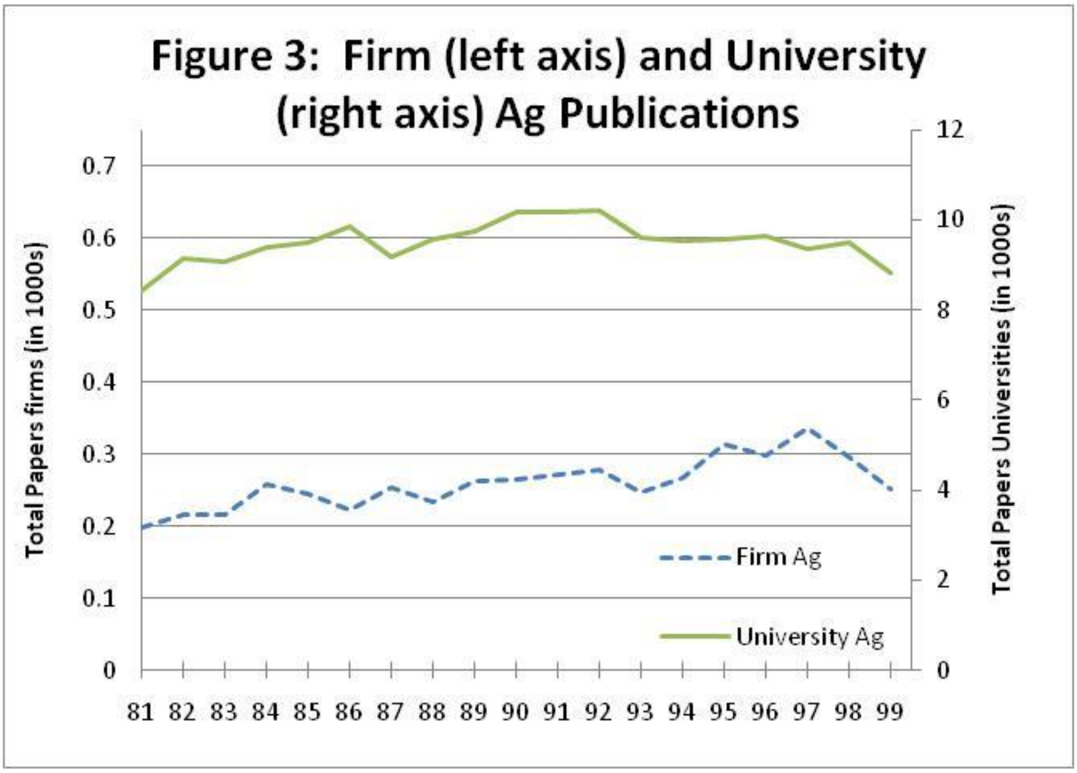


Figure 3: Firm (left axis) and University (right axis) Ag Publications
Total Papers firms (in 1000s)
Total Papers Universities (in 1000s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
2
4
6
8
10
12
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99
Firm Ag
University Ag