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

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ABSTRACT

Prior research identifies a direct positive link between the stock of public scientific knowledge and agricultural productivity; however, an indirect contribution to agricultural productivity is also possible when this stock facilitates private sector invention. This study examines how “connectedness” between the stock of public scientific knowledge and private firms influences firm-level research productivity. 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 agricultural research productivity.

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 not-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 examines how connections between the stock of public knowledge and private firms influence firm-level research productivity in agriculture. Huffman and Evenson (1993, 2006), who studied the long-run relationship between science and agricultural, show that the stock of public knowledge in "pre-technology" fields such as entomology contribute directly to agricultural productivity in the U.S. However, an indirect contribution to agricultural productivity is also possible when the stock of public knowledge facilitates private sector invention. Huffman and Evenson (1993, 2006) find a direct effect of private sector invention on agricultural productivity using private sector patents, but do not explore how private sector invention depends on the stock of public knowledge.

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 taken from the NBER-Rensselaer scientific database, allow two different forms of industry-science links to be distinguished. Citations to prior publications external to the firm and in agricultural science fields are used to capture “arms-length” knowledge flows. Public-private coauthored papers in agricultural science fields measure firm collaborations with academic researchers, which is an interactive form of connectedness. The bibliographic information is combined with data on agricultural patenting and firm-level R&D investment to analyze how connectedness influences research productivity using panel data covering the years 1986 to 1998.

In contrast to the relatively rapid growth in other life science fields, the descriptive results for 1981-1999 show that annual scientific publications in agriculture have remained roughly unchanged. While universities account for nearly all new publications adding to the stock of public knowledge in agriculture, the trends indicate that 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 outside of agriculture represent the dominant share of overall inventive and scientific output as measured by patents, publications, citations, and co-authorships.

The regression analysis 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 .026 more patents per year at the mean) while an additional co-authorship is associated with a 4.5% increase in agricultural patents (approximately

.23 more patents per year at the mean).

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 presents a simplified path diagram to illustrate the relationships between the stock of public knowledge and 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 and private agricultural invention. With state-level data for 1970-1999, Huffman and Evenson (2006) find that a 1% increase in the stock of private patents increases state multifactor productivity (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, the stock of public knowledge in agriculture might have an indirect effect on agricultural productivity by facilitating private sector invention. Our analysis of this potential link follows the conceptual model developed by Pakes and Griliches (1984). 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.

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 modes that firms use to access public scientific knowledge, collaboration through co-authorship and arms-length knowledge flows through citation have received the most attention. Zucker et al. (1998a, 1998b, 2002) use counts of articles coauthored between firm scientists and university scientists to capture tacit knowledge exchange through bench-level interaction. They argue that intellectual human capital is often tacit knowledge that is difficult to codify and communicate except through person-to-person interactions. Using a sample of "star" scientists and firms using biotechnologies, they find that various measures of firm success including patenting and products in development significantly increase with the number of co-authorship relationships.

Building on this line of research, Cockburn and Henderson (1998) examined connectedness using all co-authorships regardless of scientist status (stars or non-stars) for a sample of pharmaceutical firms. They find a positive and significant relationship between the fraction of co-authorships with universities and the number of important patents granted to the firm. Using the sample range for 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.

Gittelman and Kogut (2003) use citations to a biotechnology firm's patents as an indicator of performance. They find that the "science intensity" of a firm, as measured by backward patent citations to non-patented literature, increases performance. In other words, firms that draw more heavily on developments in academic science perform better. Gittelman and Kogut go further and include a variable that captures depth of the firm's participation in leading-edge science. They find that the quality of the firm's scientific knowledge stock, measured by the average patent cites to the firm's publications, reduces the firm's performance.

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

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

where $\ln(Agpats)_{it}$ is the natural log 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; $\boldsymbol{Connect_{i,t\text{-}1}}$ 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, but also includes covariates for non-agricultural science and self citations. $\mathbf{Z_{i,t\text{-}1}}$ 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 three 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. Because of the fairly long time dimension in the panel, Newey-West heteroskedasticity and serial correlation robust standard errors are reported. 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, $\ln(R\&D)_{i,t+1}$. 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. It is also important to keep in mind that the reduced form models we estimate do not 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 were successfully matched to 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-weighted fraction of firm patents with an agricultural application 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. Summary statistics for all of the variables used in the 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 and collaboration representing 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 agricultural scientists. A similar definition applies to "non-ag external co-authorships."

Besides annual real research and development (R&D) investment, which is required to hold firm-level inputs into invention constant, three other control variables are used in the regression analysis. Annual total employment is used in some models to hold firm size constant. Following Cockburn and Henderson (1998), real R&D expenditures per publication is used to control for the firms' "science intensity," which is related to its internal capabilities and "absorptive capacity" for externally performed research (Cohen and Levinthal 1989). We also control for the firms' "propensity to cite" as indicated by the total citations per publication in each year.

4. Descriptive and Regression Results

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, 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.[1]

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 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

[1] Note that Bureau of Economic Analysis estimates of private agricultural value added GDP grew at an average annual rate of -1.6% during this period while health care and social assistance value added GDP grew at an average annual rate of 5.1%.

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 agriculture, 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.[2] 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 or changes in scientific research opportunities. 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 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

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[2] 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.

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 (labeled as "Non-self Cite Ag"). 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 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.[3] Forty-one firms compose this group. The remaining 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.[4] 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, which might be an artifact of the historical emergence of large chemical companies in the artificial fertilizer and pharmaceutical industries (SIC 2834). It is also clear that agriculturally related patent applications, publications, citations, and co-authorships 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

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[3] 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.
4 Analysis of the backward citation data showed a clear truncation bias prior to 1986. We dropped 1999 to avoid problems with merger activity.

external citations to public agricultural science and in Ag co-authorships. As indicated by the number of Ag self cites, Merck and Monsanto relied on internal agricultural capabilities for their research more than other top Ag-users.

To better 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 of 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 fields 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 definition.) This is part of the motivation for including R&D per publication as a control variable in the regression analysis. The number of co-authorships per paper, on the other hand, increases 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.

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 avoid 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 4% 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% increase 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 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. Model (3) holds constant the overall scientific productivity of the firm as measured by total papers published per R&D dollar. This captures the firm's investment in basic science and absorptive capacity. Unlike Cockburn and Henderson (1998), it is positive and significant at the 10% level. Model (4) controls for firm size by including the log of total firm employees. Firm size is not significant, but is correlated with R&D investment as indicated by the change in the standard error for R&D between models (3) and (4). 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. We include citations per paper to control for this possibility. As shown in model (5), the firms' number of citations per paper is not significant. 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.

Table 6 shows the regression results using publication co-authorships as an alternative mode of connectedness. In addition to R&D investment, Model (1) 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 4.5% 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. When other control variables are added to the specification, as shown in model (3) – (4), the magnitude and statistical significance of agricultural external co-authorships is stable. Holding other potential determinants constant, 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 analysis explores the possibility that the stock of public knowledge in agriculture makes an indirect contribution to agricultural productivity by facilitating private sector invention. Using detailed bibliometric data, the degree of "connectedness" between firms and the stock of public knowledge is analyzed using information from both "arms-length" citations and public-private collaboration through co-authorship on scientific papers. Our results for agriculture using co-authorships are consistent with the findings of Zucker and Darby (1998b) who analyzed firms using biotechnologies and those of Cockburn and Henderson (1998) who analyzed a sample of pharmaceutical firms. Although these prior studies did not analyze citations, our finding that citations have a smaller marginal effect on research productivity than co-authorships fits with prior arguments that interactive exchange of knowledge between public and private researchers is a more effective means of transferring intellectual capital. However, co-authorship is also more costly and optimal firm behavior will depend on the ratios of marginal benefits to marginal costs which were not estimated in this analysis.

Our findings reject a more insular conception of how firms develop inventions. Firms' citations to their own publications have smaller, statistically insignificant effects on the generation of new patent applications while citations to publications by authors in different institutions increase patenting by a statistically significant and non-trivial amount. Since the majority (typically more than 90%) of open science is published by university researchers, this suggests that university research has applicability to targets of private sector research and value that they do not necessarily capture in formal technology transfer agreements.

During the period in this study, the agricultural sector was undergoing significant technological change, including commercialization of the first genetically modified crop varieties by several of the firms in our sample.[5] These technological advances drew widely on science and technologies developed in other fields, especially biological and medical science. Despite the greater volume of research in these areas – attributable to greater public funding – inventive productivity was most strongly associated with specifically agricultural sciences. Evidence for spillovers (see for instance Jaffe, 1986) from other scientific disciplines was not significant in this study. It is possible that fundamental, basic research from other areas entered through agricultural science publications, but science from medical, biological, and other scientific fields did not produce significant effects. Likewise, agricultural open science did not extensively "spill out" to other industries, based on the observation that citations and collaborations involving agricultural science was largely concentrated among a small minority of

[5] The first genetically modified crops for commercial sale in the US were planted in 1996; genetically modified varieties are now planted on more than half of cropland acres. (ISAAA, 2010.)

firms just in our sample of the chemical and allied products (SIC 28) sector.

Although these regression models hold a number of other important factors constant, our empirical analysis does not implement a structural model of citation or co-authorship. A model that incorporates the marginal costs of maintaining connectedness to open science and not just its equilibrium marginal benefits would provide stronger evidence for the model of firm behavior in open science that we propose. Also, MacRoberts and MacRoberts (1996) raise concerns about the validity of citations as a measure of scientific influence, although the weak effects of self-citations and stronger, statistically significant econometric evidence address some of these concerns.

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Table 1: Descriptive Statistics (399 firm-year observations, 1986-1998)

Variable	Mean	Standard Deviation	Minimum	Maximum
Ag Patent Apps (t)	5.11	6.34	0.23	44.58
Real R&D(t-1) [millions $]	421.90	436.22	1.76	2385.51
Employment (t-1) [1000s]	29.43	29.70	0.11	146.02
Ag External Citations(t-1)	21.56	39.49	0	305
Non-Ag External Citations(t-1)	1502.28	1962.68	0	10105
Internal Citations(t-1)	345.88	488.24	0	2949
Ag External Coauthorships(t-1)	2.00	3.64	0	28
Non-Ag External Coauthorships(t-1)	57.68	62.26	0	305
Papers per R&D dollar(t-1)	0.65	1.40	0.01	14.80
Total Citations per Paper(t-1)	9.26	6.50	0	29.26

All variables are in levels. Data is an unbalanced panel of 33 firms with an average of 12.1 years per firm.

Table 2: Contributuions 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)

		R&D	All	Ag	Total	Ag	Total Cites	Self	Non-self	Self Cite	Non-self Cite	Ag	Non-Ag	External Cites	Coauthorships
GROUP	**Years**	**Intensity**	**Patents**	**Patents**	**Pubs.**	**Pubs.**	**per Pub.**	**Cite Ag**	**Cite Ag**	**Non-Ag**	**Non-Ag**	**Coauthorships**	**Coauthorships**	**per Pub.**	**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

		R&D	All	Ag	Total	Ag	Total Cites	Self	Non-self	Self Cite	Non-self Cite	Ag	Non-Ag	External Cites	Coauthorships
GROUP	**Years**	**Intensity**	**Patents**	**Patents**	**Pubs.**	**Pubs.**	**per Pub.**	**Cite Ag**	**Cite Ag**	**Non-Ag**	**Non-Ag**	**Coauthorships**	**Coauthorships**	**per Pub.**	**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 Agricultural Research Productivity (1986-1998): Firm-level Fixed Effects

Dependent Variable:	(1) Ag Patent Apps	(2) Ag Patent Apps	(3) Ag Patent Apps	(4) Ag Patent Apps	(5) Ag Patent Apps
Ag External Citations(t-1)		0.005	0.005	0.005	0.005
		(0.0016)***	(0.0016)***	(0.0016)***	(0.0016)***
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)		-0.0003	-0.0002	-0.0002	-0.0001
		(0.0003)	(0.0003)	(0.0003)	(0.0003)
ln R&D (t-1)	0.509	0.485	0.620	0.639	0.621
	(0.086)***	(0.083)***	(0.113)***	(0.153)***	(0.160)***
Papers per R&D Dollar(t-1)			0.071	0.073	0.071
			(0.038)*	(0.039)*	(0.040)*
ln Emp(t-1)				-0.022	-0.023
				(0.133)	(0.133)
Citations per paper(t-1)					0.009
					(0.023)
Year Dummy Variables	Y	Y	Y	Y	Y
R-squared	0.1985	0.2272	0.2319	0.2319	0.2323
Root MSE	0.6718	0.6597	0.6577	0.6576	0.6575
Observations	399	399	399	399	399

*** 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, lag length=3).
Fixed effects regressions were performed using the "xtivreg2" STATA command developed by Schaffer(2010).

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

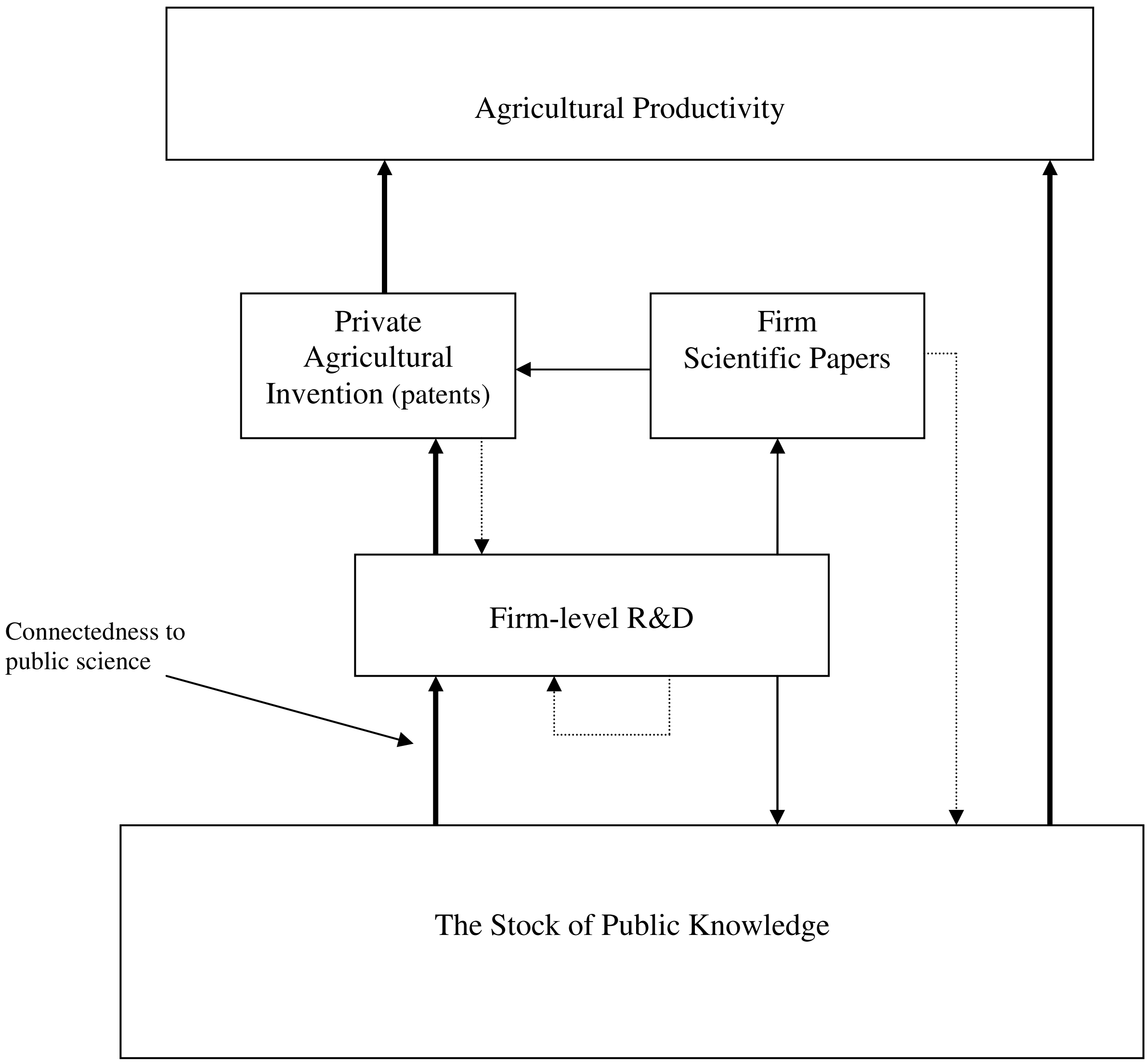
Dependent Variable:	(1) Ag Patent Apps	(2) Ag Patent Apps	(3) Ag Patent Apps	(4) Ag Patent Apps
Ag External Co-authorships(t-1)	0.045	0.045	0.044	0.043
	(0.012)***	(0.012)***	(0.012)***	(0.012)***
Non-Ag External Co-authorships(t-1)	0.0014	0.0007	0.0007	0.0003
	(0.0014)	(0.0014)	(0.0014)	(0.0015)
ln R&D (t-1)	0.501	0.650	0.689	0.642
	(0.081)***	(0.103)***	(0.141)***	(0.150)***
Papers per R&D Dollar(t-1)		0.083	0.086	0.079
		(0.036)**	(0.036)**	(0.038)**
ln Emp(t-1)			-0.048	-0.046
			(0.136)	(0.134)
Citations per paper(t-1)				0.017
				(0.022)
Year Dummy Variables	Y	Y	Y	Y
R-squared	0.2209	0.2276	0.2278	0.2292
Root MSE	0.6624	0.6595	0.6594	0.6588
Observations	399	399	399	399

*** 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, lag length=3).

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

Figure 1: Simplified path analysis diagram of agricultural productivity



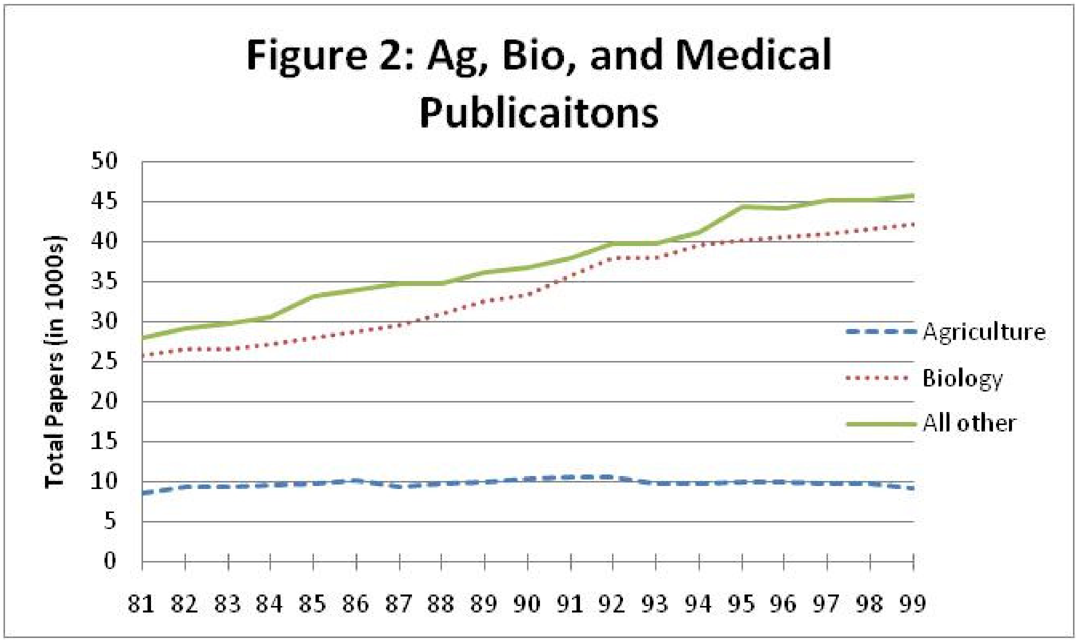


Figure 2: Ag, Bio, and Medical Publicaitons
Total Papers (in 1000s)
50
45
40
35
30
25
20
15
10
5
0
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99
Agriculture
Biology
All other

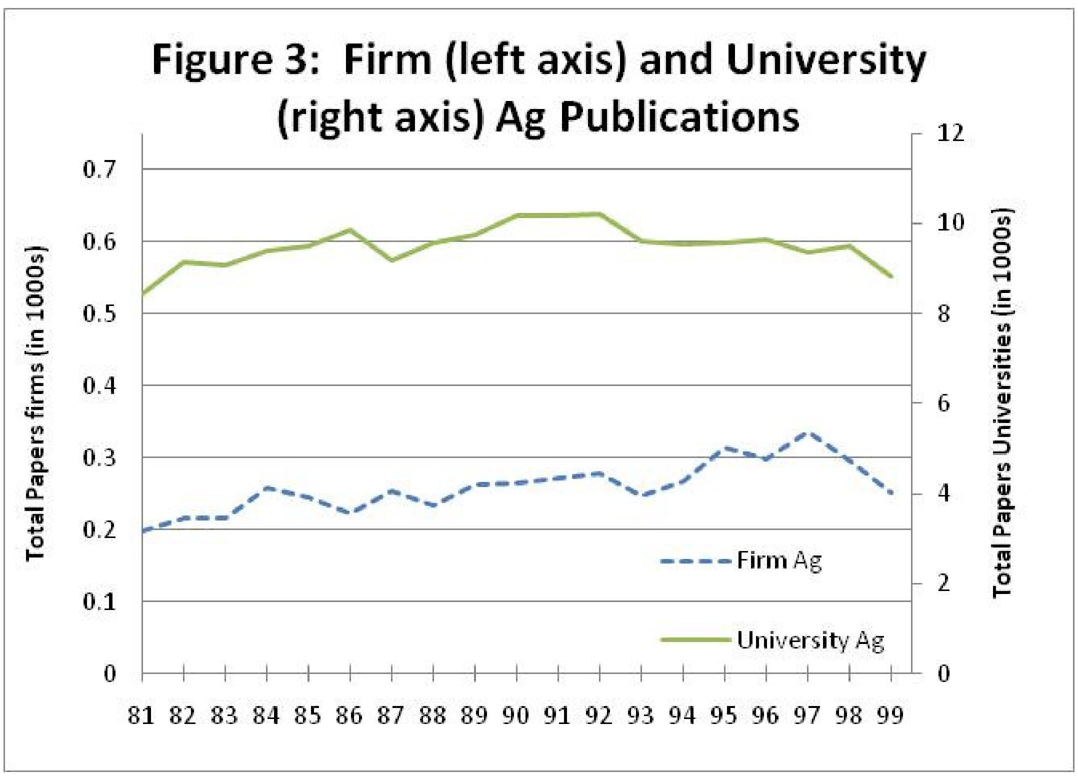


Figure 3: Firm (left axis) and University (right axis) Ag Publications
Total Papers firms (in 1000s)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Total Papers Universities (in 1000s)
12
10
8
6
4
2
0
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99
Firm Ag
University Ag