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**THE ENDOGENEITY OF ACADEMIC SCIENCE TO LOCAL INDUSTRIAL
R&D: EVIDENCE FROM THE AGRICULTURAL BIOTECHNOLOGY
INDUSTRY**

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Abstract

This paper explores the impact of local industry R&D upon the rate and direction of academic research in the regional innovation system. I argue that the impact of local industrial R&D upon the research productivity of nearby universities hinges upon university's boundary-spanning capacity, which facilitate and incentivize the bilateral transaction between industry and academia. I find support for my argument in the setting of agricultural biotechnology industry, showing that after the agricultural incumbent's entry into plant biotechnology R&D, nearby universities which had stronger boundary spanning capacity experienced a greater boost in the plant-biotechnology related publication output compared to other nearby universities.

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ABSTRACT

This paper explores the impact of local industry R&D upon the rate and direction of academic research in the regional innovation system. I argue that the impact of local industrial R&D upon the research productivity of nearby universities hinges upon university' s boundary-spanning capacity, which facilitate and incentivize the bilateral transaction between industry and academia. I find support for my argument in the setting of agricultural biotechnology industry, showing that after the agricultural incumbent' s entry into plant biotechnology R&D, nearby universities which had stronger boundary spanning capacity experienced a greater boost in the plant-biotechnology related publication output compared to other nearby universities.

INTRODUCTION

The recent view of “entrepreneurial university”, or “mode 2” university has put academic institution at the forefront of active economic and political discourses. It is widely claimed that universities are the key infrastructure that undergirds the growth of innovation and entrepreneurship in nations (Mowery, 1992; Nelson, 1993), as well as regions (Hausman, 2012; Zucker et al., 1998) .

Many policy practitioners believe that the economic success of industrial clusters like Silicon Valley or Cambridge’ s biotechnology cluster can be replicated by bringing up universities like Stanford University and MIT. New York City’ s mayor Michael Boomborg seems to be one of them – the mayor recently invited top-notch universities to enter the bidding for a new campus for engineering and applied sciences, with a hope to transform the city into the next Silicon Valley.

This kind of policy plan owes itself to the vast literature that supports the existence of positive geographic spillovers of university research on the local industry (Anselin et al., 1997; Jaffe, 1989). The commonly drawn conclusion is that if we build more universities or increase university research spending in the region, the increased academic knowledge spillovers will lead to a boost in industrial innovation and entrepreneurship within the regional innovation system.

However, another important question is what drives universities to produce knowledge in areas of science that are relevant to industrial R&D. Whereas the existing literature and policy discourses have emphasized the role of university research as an important *input* to the regional innovation system, less attention was given to the production of academic knowledge as an

output of the system – *i.e.* how a region’ s innovative milieu (Breschi and Lissoni, 2001) can shape the university’ s production of scientific knowledge. Even if two universities were to have a same combination of internal researchers and resources at a point in time, the type and extent of academic knowledge produced by each may differ in the long run, depending upon the industrial and socioeconomic aspects of the local environment that the university researchers are embedded in. Contrary to the general assumption that university science unilaterally shapes the local industry, this study explores to what extent and how university science can be shaped by the local industry and institutional infrastructure.

Although a group of scholars have alluded to the existence of bilateral, co-evolutionary feedback between university science and industry technology (Etzkowitz et al., 1998; Murmann, 2013; Rosenberg, 1982), the impact of industry upon academic research in the local milieu still remains an understudied topic. Although a number of studies examined the impact of industry collaboration or patenting upon research outcome at the individual level (Azoulay et al., 2009; Calderini et al., 2007; Fabrizio and Di Minin, 2008), few studies have looked at this topic in a broader research context that incorporates factors like geographical proximity or socioeconomic institutions. My research fills the gap by exploring the following questions: How does geographical proximity to industrial R&D shape the rate and direction of academic research? Under what circumstances will local industrial R&D have an impact upon the rate and direction of academic research?

In this study, I argue that the impact of local industrial R&D upon the research productivity of nearby universities hinges upon university’ s boundary-spanning capacity. In other words, universities that are geographically proximate to the loci of industrial innovation will develop higher research productivity in scientific fields that are relevant to the industry, if

they have institutions and resources that incentivize and facilitate active boundary-spanning between academia and industry. Boundary-spanning capacity would encompass broad institutional infrastructure and normative system which incentivizes university researchers to pursue industry-relevant science, as well as induces industry to invest in the university. For example, a university with strong boundary-spanning capacity would have a tenure system or institutional culture that values applied, commercial research and academic patenting as much as basic science, the institutional infrastructure such as technology transfer office, spin-off incubators and industry collaboration and training programs. Unless a university has such capacity, having an exposure to industrial R&D even in close geographical proximity would not have as meaningful an impact.

Empirically, the bi-directional nature of local industry-university relationship poses an identification challenge: the selection bias and simultaneity make it difficult to disentangle the impact of local industry on local academia from vice versa. In a typical science-based industry, companies often choose to locate in those regions where academic scientists are already doing or possess a potential for higher quality research in the industry-relevant fields of science. It may also be the case that breakthrough research by local scientists encourages geographically proximate firms to pursue follow-on R&D to exploit these new discoveries. This results in a biased estimate of the treatment effect, as the treated university, which is colocated with the corporate R&D site, is likely to be different from a randomly chosen, average university in terms of industry-relevant research conducted at the point of treatment or in the future.

This study exploits a research setting that allows us to get around this identification challenge, the agricultural biotechnology industry. I specifically focus on the role of major anchor tenant firms in the U.S agriculture industry, which pioneered the scientific research in

plant biotechnology before the entry of land grant universities and have continued to be dominant players in R&D – Monsanto, Du Pont, Syngenta and Dow Agrosiences. Unlike new ventures or greenfield subsidiaries that were born to exploit local university spillovers in biotechnology, the anchor tenant firms entered into biotechnology R&D at or near their established locations in the non-biotechnology businesses. The issue of endogenous treatment is mitigated in this setting because these locations had been determined long before the companies could have anticipated their future entry in plant biotechnology.

Exploiting this setting, I develop a DDD (difference-in-difference-in-differences) estimation of the impact of the colocated industry's entry into plant biotechnology R&D upon the rate and direction of scientific research in local universities. I look at whether the entry of agricultural anchor tenant firms into the plant biotechnology R&D led to an increase in the publication outcomes of nearby universities in plant-biotechnology-related topics like plant molecular genetics and plant cell biology. I carefully control for other biases by coarsened-exact matching treated and control universities on pre-treatment characteristics.

Most importantly, I focus on examining whether the boundary-spanning capacity of the nearby universities leads to differential impact of local industry R&D upon publication outcome. Due to the difficulty of collecting institutional-specific microdata, I use the Pre-1980 stock of non-biotechnology patents and the existence of a medical school. The assumption here is that the fact that the university had been an early pioneer in academic patenting (even prior to the Bayh-Dole Act) or have had a medical school would signal that 1) the university must have had an orientation for industry-relevant and application-oriented science, 2) the university must have built from the early exposure to technology transfer and industry collaboration more systematic infrastructure to aid industry boundary-spanning.

The results from fixed-effect Poisson regressions show that having a strong boundary capacity, proxied by whether the university had been a top 5% patentee before 1980 or having a medical school, makes a local university respond stronger to local industrial R&D. Colocated universities with a medical school experience a 17% boost in plant biotechnology publications compared to universities with a non-medical school. Treated universities which had been the top 5% patentee experienced a 140% boost in the publication outcome, compared to other treated universities with less prior patents.

This study provides both scholarly and policy implications to the burgeoning literature in the economics of regional innovation. This study fills a gap in the literature of regional knowledge spillovers by highlighting the understudied aspect of co-evolutionary feedback between industry and academia, the impact of local industry R&D upon academia. To my knowledge, this study is one of the first empirical attempts to quantitatively identify the impact of local industry R&D upon academia at the university level. This study provides a policy implication for the practitioners about the important role of boundary-spanning capacity in promoting a synergistic convergence between local industry and academia.

LITERATURE REVIEW AND HYPOTHESES

The Endogeneity of Academic Science to Industrial Innovation and Technology

The relationship between academia and industry within regional innovation system often boils down to a classic chicken-or-egg question – such as the one of “*Whether Stanford fueled the tech explosion or the industry put Stanford on the map*” (Wolfe, 2012). Whereas industrial innovation is influenced by the amount and quality of research produced by local universities,

the rate and direction of academic research itself is also simultaneously influenced by the local industrial context. While both lines of causality may operate, systematic empirical research has been heavily biased towards the former (Anselin et al., 1997; Audretsch and Feldman, 1996; Hausman, 2012; Jaffe, 1989; Zucker et al., 1998). These studies mainly argue that academic knowledge is diffused or transferred to local industry for application and commercialization, acting as an important impetus for growth in industrial innovation and entrepreneurship in the region.

While trying to measuring the impact of geographically localized knowledge spillovers from academia to industry, most empirical studies implicitly assume academic knowledge in a region as an exogenously determined input. Often overlooked or abstracted away in these studies is the reverse relationship - that academic knowledge within a regional innovation system can be an endogenous output of industry and institutions within the region¹.

In part, this gap in the empirical literature may be (implicitly) driven by the traditional dominance of “linear model” of science and technology, which regards academic science to unilaterally shape and support industry innovation (Bush, 1945)². The linear model assumes that basic science in the academia precedes the applied R&D and innovation in the industry, ignoring that formation of scientific questions (even those that may seem basic under the dichotomy of basic vs. applied research) can be guided by simultaneous pursuit for industrial application (Rosenberg, 1982). This view has been strengthened by the political rhetoric of pure science, which considers applied research dependent on and inferior to basic research (Godin, 2006).

¹ For example, in Zucker et al. (1998), the geographical distribution of academic stars is considered as exogenously determined. In other words, the study does not consider why certain scientists in certain regions became academic stars in biotechnology. Although Jaffe (1998) and Anselin et al. (1997) allow industry R&D expenditure to affect university R&D expenditure at the regional level, this is done more for the sake of econometric estimation rather in consideration of the underlying relationship in knowledge creation.

² Godin (2006) provides a comprehensive review of the literature on the linear model of innovation.

According to this traditional view, basic research is considered to be solely guided by internal norms of the academic society, such as intrinsic motivations and peer-group esteem (Dasgupta and David, 1994; Polanyi, 2000).

On the other contrary, a group of scholars have emphasized the bilateral, co-evolutionary feedback from the external world to academic science (Etzkowitz et al., 1998; Murmann, 2013; Rosenberg, 1982). According to this view, the creation of scientific knowledge is guided by technological needs of the industry, as well as overall socioeconomic concerns that may be external to the academic realm. For example, the development of solid state physics as an academic discipline was driven by the industry need to understand the transistor effect and develop better semiconductors (Rosenberg, 1982).

This view is complemented by recent empirical studies that show individual academic scientists are also motivated by incentives other than intrinsic motivation and freedom of research, which are traditionally thought to be the drivers of “pure”, Mertonian science. Academic scientists of today have adopted patenting and commercialization as either a viable norm that co-exist or contend with the traditional Mertonian norms (Azoulay et al., 2009; Lam, 2011; Murray, 2010). Not only are scientists motivated by now heightened status associated with academic patenting and industry affiliation, they are also directly motivated by monetary incentives that the industry and patenting regime can offer (Lach and Schankerman, 2008; Lam, 2011).

My study complements the prior studies by highlighting the relationship within a regional innovation system: whether the rate and direction of academic research is shaped by local industrial R&D within geographical proximity. Although studies have shown that university research has a positive impact on the rate and direction of innovation in neighboring industries

(Furman and MacGarvie, 2007; Hausman, 2012; Zucker et al., 1998), few studies have explored the reverse relationship in a geographical context.

The Role of Geographical Proximity and Boundary-Spanning Capacity in the Relationship between Industrial R&D and Academic Research

Academic researchers of the current post-Bayh-Dole era span the ever more permeable boundary between university and industry, through a variety of channels including meetings and conferences, sharing of equipment and materials, hiring of personnel, research collaboration, industry grant and fellowship, academic consulting, contract research, technology transfer and venture spin-off (Agrawal, 2001; Bercovitz and Feldman, 2006). The research trajectory of university scientists respond to such opportunities and incentives provided by the industry.

The literature provides us a number of reasons to expect stronger interactions between the companies and universities that are more geographically proximate to each other. On the one hand, industry may have an incentive to seek local academic partners for contract research and joint collaboration because geographical proximity lowers coordination, monitoring and communication costs (Kraut et al., 1988). They may be motivated by the fact that the lower opportunity cost of travelling over shorter distance can lead to more novel experimentation and recombinations of ideas (Catalini, 2012). Firms can also assist academic research by sharing valuable resources like expensive machinery or rare stem cell lines without strings attached (Evans, 2010), and such relationships may be strengthened with geographical proximity by reciprocal trust and social bond that reside in the local region (Saxenian, 1996).

On the other hand, academics also have an incentive to align their research towards local industry, as their social embeddedness within the regional community induces them to identify

and exploit professional or entrepreneurial opportunities within geographical proximity. Although the labor market for science and engineering operates at a national scale in the long run, the embeddedness of people in the local labor and social network limit the effective scope of labor market to the regional level (Almeida and Kogut, 1999; Kerr and Lincoln, 2010; Topa, 2001). This gives a potential boundary-spanner in the academia an incentive to pre-align her research with the local industry, so that if she were to leave the academia, she can more easily find a job or start a company in the local labor market, as one can better leverage their social ties to mobilize important information and resources when they reside closer to those resources (Stuart and Sorenson, 2003).

The above discussion implies that the impact of industry R&D will have a stronger positive impact upon the rate and direction of industry-relevant research among local universities, given that local universities will interact more closely with the industry by the virtue of geographical proximity. However, an important caveat is that university' s inteaction with the industry itself is shaped by the institutional context of individual universities. I argue that local industrial R&D will have a stronger positive impact upon university research in the industry-relevant fields, if the university has the institutional infrastructure and norms that facilitate and incentivize academic scientists to span the industry boundary, which I refer to as *boundary-spanning capacity*.

In the organizational literature, boundary-spanning individuals refer to those that are not only competent in their internal jobs but also able to acquire important resources and information from the external world (Aldrich and Herker, 1977; Friedman and Podolny, 1992; Tushman and Scanlan, 1981). In the academic realm, boundary-spanning activities of academic scientists include filing academic patents and engaging in technology transfer, collaborating with industry

in joint projects or contract research, serving on scientific advisory boards, or joining ventures (Azoulay et al., 2009; Ding et al., 2012; Evans, 2010; Toole and Czarnitzki, 2007).

University' s institutional arrangements³ , such as incentives, behavioral norms, and role expectations of academic scientists with regard to industry involvement, play a crucial role in the endogenous relationship between industry and academia by shaping the individual incentive and opportunities to engage in such boundary-spanning activities. For example, a university with strong boundary-spanning capacity would have a tenure system or norms and culture that values applied, commercial research and academic patenting as much as basic science, the institutional infrastructure such as technology transfer office, spin-off incubators and industry collaboration/training programs.

University' s boundary-spanning capacity works bi-directionally, both incentivizing academic researchers to pursue industry-relevant science and simultaneously inducing industry to invest in the university. An academic' s decision to delve into industry-relevant research is not merely determined by the amount of potential pecuniary payoff, but also by whether the university has the institutional capacity to support and incentivize such diversion. Concurrently, the industry' s decision to fund and sponsor universities is not simply determined by whether the universities have the best-quality researchers, but also by whether the universities have such institutional capacity which enable the industry to reap the returns to the investment in an efficient manner.

Unless a university has such capacity, having an exposure to industrial R&D even in close geographical proximity would not have as meaningful an impact. I therefore make the prediction:

³ The term “institutions” here is used in a sociological sense and refers to the social structure and mechanisms within an organization. It should be distinguished from “academic institutions” or “educational institutions”. In this study, I use the term “university” for the latter.

Hypothesis: Industrial R&D in the focal university' s geographical proximity (“local industrial R&D”) has a greater positive effect upon the university' s research in industry-relevant fields of science if the university has strong boundary-spanning capacity.

RESEARCH SETTING AND DESIGN

Only a small empirical literature cleanly identifies the industry-to-academia feedback by addressing issues of selection and endogeneity (Furman and MacGarvie (2007) is one of such few empirical works). First, it is possible that private firms will choose to locate in those regions where academic scientists are doing related work, and they may be particularly interested in regions where such scientists have a willingness or ability to also become academic entrepreneurs (this would result in a “selection effect”). Second, it may be possible that breakthrough research by local scientists encourage geographically proximate firms to pursue follow-on research to exploit these new discoveries (this would result in endogeneity through “reverse causality”). Although these fundamental issues of inference are acknowledged in the empirical literature, few of them have found exogenous variation to address them.

In an ideal experiment, one would randomly locate industrial R&D laboratories, independently of research quality or trajectory of academic researchers and institutions in the given locations, then compare the impact of industry co-location upon the future evolution of academic research in the treated regions against the controls. Or, one would initiate a certain type of industrial R&D project in a randomly selected group of existing R&D locations and observe the evolution of local academic research in those regions.

However, since such randomized experiment is virtually infeasible, an alternative identification strategy would be to find cases in which the topic of industrial R&D had been determined as a quasi-exogenous shock to the local university research. Another strategy is to compare the treated universities with valid counterfactuals that would otherwise have followed the same trajectory in the output variable, after conditioning on other necessary controls (Greenstone et al., 2010). In order to overcome the conundrum, I combine the two identification strategies and explore my research questions in the setting of agricultural biotechnology industry.

Identification Strategy: Exploiting the Entry of Agricultural “Anchor Tenants” into Plant Biotechnology R&D

The main intuition in my identification strategy is to exploit cases in which the existence of industrial R&D has driven the rise of academic science in the region, rather than vice versa. This is exactly the opposite approach of Zucker et al. (1998), in which the authors look at regions that the existence of intellectual human capital has driven the growth of local industry.

Agricultural biotechnology industry makes an ideal setting for this identification strategy, because unlike the case of medical biotechnology in which the birth of industry followed or coincided with the rise of academic science, the use of biotechnology in agriculture had been driven by the initiative of existing incumbent companies, even prior to the land-grant universities (Kenney, 1986). Particularly, I leverage the fact that the agricultural biotechnology R&D had been driven by a select number of anchor tenant firms (Agrawal and Cockburn, 2003) – large, local, R&D intensive firms that have resided in their regions since long before the advent of biotechnology and remain as active innovators in the original locations.

In the early phase of agricultural biotechnology industry, de novo startups and greenfield subsidiaries were founded near major universities and their academic stars. Such examples include de novo agricultural biotechnology startups like Calgene (founded in 1980 by Ray Valentine, a plant geneticist at University of California Davis) and Mycogen (founded in 1982 by Andrew Barnes, a biochemist in San Diego), as well as greenfield subsidiaries of diversifying entrants like Agracetus (founded in 1981 by the pharmaceutical biotechnology firm Cetus under the helm of Dr. Winston Brill, a microbiologist recruited from University of Wisconsin).

In contrast, the central R&D locations of the incumbent anchor tenants were not driven by the availability of university scientists in biotechnology-related disciplines. Such anchor tenants include traditional seed breeders as well as diversifying incumbents from other (broadly defined) agricultural industry, such as agrochemicals and animal health. As they had been previously operating in non-biotechnology industries since long before the inception of agricultural biotechnology, their locations had been chosen for reasons that are mostly exogenous to the development of academic research in modern biotechnology. The locational inertia kept these firms at or near their traditional R&D locations even after the technological discontinuity. In this study, I focus on five such incumbent companies in the U.S. agriculture industry: Monsanto, Du Pont, Ciba Geigy (now Syngenta), Pioneer Hi-Bred (now part of Du Pont), and Elanco (now Dow Agrosciences).

The Historical Evolution of the Agricultural Biotechnology Industry

Agricultural biotechnology refers to a broad set of scientific and technological knowledge and techniques to improve the agricultural yield of plants and animals (for the purpose of this study, the focus will be specifically on plant biotechnology). The main tool in modern

agricultural biotechnology is genetic engineering, which refers to the introduction of new traits into organisms by manipulating their genetic elements. For example, crops can be genetically engineered to withstand drought, insects or disease (e.g. Bt cotton produces natural insecticide). They can also be engineered to provide certain nutrients or phytochemicals (e.g. Golden rice is genetically engineered to contain more beta carotene).

Genetically engineered crops can be either a substitute or complement to the existing agrochemicals. For example, you can engineer a crop to eliminate the need to use insecticides (making GMO crop a substitute to agrochemicals), or you can engineer it to be immune to a certain compound in herbicide so that farmers can spray the herbicide without damaging the crop (making it a complement). Either way, it meant a set of whole new competitive opportunities for both seed breeders and agrochemical manufacturers.

The growth of agricultural biotechnology was fueled by two major events in 1980, which left important marks in the U.S. patenting regime: the Supreme Court's ruling on *Diamond vs. Chakrabarty* case and the enactment of Bayh-Dole Act. The former event provided a legal ground so that genetically modified organisms to be patented, and the latter event promoted the participation of university researchers by allowing federally funded research to be patented.

Industry entrants in agricultural biotechnology can be categorized as de novo startups, incumbent agriculture firms, and diversifying firms from related industries, such as chemical or pharmaceutical (Moeen, 2013). De novo startups (e.g. Calgene, Mycogene) entered the industry with an intention to capitalize on their new scientific knowledge in the growing market for genetic engineering. On the other hand, traditional agriculture firms in seed breeding and hybridization (e.g. Pioneer, Dekalb) also entered into genetic engineering R&D to protect and exploit their existing technological assets. Although genetic engineering itself was technological

discontinuity to the old technology, their breeding techniques and “germplasms” still remained as co-specialized, complementary assets that genetic engineering companies need for successful commercialization (Teece, 1986). Last but most importantly, diversifying entrants from related industries, especially chemicals (e.g. Monsanto, Ciba Geigy), entered the agbio industry with technological prowess and deep pockets. They had a strong incentive to enter into genetic engineering because the new technology radically changed the way that herbicides and pesticides could be marketed.

After the initial introduction of genetic engineering technology, the agricultural biotechnology industry went through a very long period of incubation until the first commercial GM food was introduced to market in 1994 (Calgene’ s Flavr Savr tomato). At the same time, the industry has also undergone a series of large-scale acquisitions and vertical integration due to the inhibiting cost and risk of developing and marketing a genetic trait. As of today, only a handful of players, mostly agrochemical multinationals from the U.S and Europe, remain as active and dominant players in the R&D landscape of agricultural biotechnology. In contrast, due to the lack of market power, most de novo startups eventually ended up getting acquired by multinational firms and failed to build a strong industry presence in the region, enough to impact local universities.

Who Are the Agricultural “Anchor Tenants”

I apply the following conditions to identify the anchor tenants and their R&D locations, which will be the loci of treatment in my empirical testing. To begin with, the anchor tenants must show a record of prolonged, intensive engagement in plant biotechnology R&D, enough to have an impact upon scientific realms. This is evidenced by the amount of plant biotechnology

patents and academic articles in topics relevant to plant biotechnology. They also need to have chosen the locations of R&D due to locational inertia, rather than in anticipation of university knowledge spillovers in biotechnology. First, the anchor tenants must have been founded in the U.S. before the year of 1980 when two major events occurred in the history of genetic engineering. Second, the anchor tenants must have remained at or near their previous R&D locations, rather than spinning off a new subsidiary or setting up a new laboratory in a distant location near high-caliber research universities. Third, there must not have been any new plant biotechnology ventures founded in these R&D locations prior to the anchor tenant' s entry. This confirms the fact that the local industry' s entry into biotechnology had been driven by a strategic incentive to respond to an external shock, rather than scientific opportunities that had been internal to these locations.

In order to identify the active players in the R&D landscape, I start by examining the USDA agricultural biotechnology patent data, which includes agricultural biotechnology patent grants between 1974 and 1998 (Refer to Table 1). The industry entered a consolidation phase in the late 1990s, and all major players had entered the U.S market by then. From the database, I identify the major industry contributors in plant biotechnology R&D, which satisfy the definition of anchor tenant. Among the 20 top patent assignees, I exclude de novo startups (Mycogen, Calgene, New England Biolabs) and multinational companies that entered U.S after 1980s (Bayer AG, Hoescht, BASF). Dekalb, Asgrow and American Cyanamid were dropped because they ceased their R&D efforts in plant biotechnology after acquisition or exit during the 1990s. As a result, only five companies satisfy the definition of anchor tenants: Monsanto, Du Pont, Ciba Geigy, Pioneer Hi-Bred and (Dow)Elanco.

Monsanto. Monsanto is one of the biggest multinational agrochemicals and agricultural biotechnology company in the world. John Francis Queeny founded Monsanto with the idea of saccharine manufacturing in St. Louis in 1901. Before its entry into genetic engineering, it had diversified into pesticides, dioxins and plastics. Its main product in the agricultural business was herbicide Roundup (glyphosate), which so far has been the one of the most widely used herbicide in the U.S. In 1981, a molecular biology group was set up and biotechnology was established as Monsanto's strategic research focus. Ever since, Monsanto has been one of the most active players in the plant biotechnology R&D race and now the world's biggest seed company, controlling 27% of the proprietary seed market as of 2013. Although Monsanto as a whole operates multiple R&D sites after the acquisition of Calgene, Agracetus and Dekalb, Monsanto's main R&D headquarters has been located in Chesterfield, right next to its original founding location in St. Louis.

Du Pont. E.I. du Pont de Nemours and Company, henceforth Du Pont, was founded in 1802 near Wilmington, Delaware as a gunpowder manufacturer. It had chosen the current location because of easy access to waterpower and trees (Furman and MacGarvie, 2009). It diversified into other areas of business in the early 20th century, exploiting its capability in chemicals. The company had been in the agrochemicals business since 1928, mainly as a manufacturer of herbicide and pesticide. In the early 1980s, the company entered into agricultural biotechnology R&D about the same time as Monsanto and is now a member of "Big 6" (Monsanto, Du Pont, Syngenta, BASF, Bayer, Dow) in the global seed industry. Du Pont's agricultural R&D has been conducted in Du Pont Experimental Station in Wilmington.

Ciba Geigy. Ciba-Geigy is a predecessor of Syngenta in the early 1980s. Ciba-Geigy was originally a Swiss-based multinational chemicals company, born after the merger of Ciba and

Geigy. The U.S. agricultural division of Ciba-Geigy Chemicals had been located in Greensboro, North Carolina from the early 1970s. Ciba-Geigy entered the plant biotechnology R&D in 1983, setting up a biotechnology laboratory in Research Triangle Park, proximate to its original agrichemicals division in Greensboro. Although Ciba-Geigy's new location was chosen to have a long-term presence near the RTP's research universities, cutting-edge plant biotechnology were not immediately available in RTP at the point of entry. Instead, they hired Mary-Dell Chilton, a renowned plant biotechnology researcher at Washington University in St. Louis. Ciba-Geigy was later merged with Sandoz to form Novartis, then its agricultural biotechnology business was spun off as Syngenta.

Pioneer Hi-Bred. Pioneer Hi-Bred, a breeder and distributor of hybrid corn, was founded in Des Moines, Iowa in 1926. It had been the leading expert in traditional breeding and cross-hybridization and owned seed germplasms, the complementary asset to genes. However, their R&D capability was distinct from molecular biology required in the modern plant biotechnology. Pioneer Hi-Bred established a plant biotechnology team in 1989. It was acquired by Du Pont in 1999, but it has remained active in research in its original location. Its R&D site has been located in Johnston, Iowa near its original founding location.

(Dow)Elanco. Elanco is the agricultural division of Eli Lilly and Company, a major pharmaceutical company based in Indianapolis since 1870s. Formed in 1954, Elanco's main business had been the veterinary pharmaceuticals as well as agrichemicals such as insecticide, herbicide and fertilizers. In 1989, Elanco's full-fledged engagement in plant biotechnology research took off when its plant science division entered into joint venture with the Dow Chemical Company. Although Eli Lilly divests out of DowElanco partnership in 1997 and it becomes Dow Agrosciences of today, its R&D headquarters has been based in Indianapolis since

Elanco's founding in 1954. Dow Agrosiences grew to be one of the Big 6 of agricultural biotechnology industry, acquiring Mycogen and Cargill's North American seed business

DATA AND EMPIRICS

Sample

My sample of universities comes from the NSF Survey of Graduate Students and Postdoctorates in Science and Engineering (GSS survey) between 1972 and 2009. I dropped from the initial sample professional and special-purpose schools such as seminaries, military schools, osteopathic or dental schools, as well as schools located in Puerto Rico. In the case of public university systems which include separate and distinct academic institutions that operate in multiple campuses, such as University of California or University of Texas, each stand-alone university is counted as one unit of observation. I further trimmed the sample by only examining research-oriented schools that have been active in the realms of scientific research and publishing. Research I, Research II, Doctorate-Granting I, Doctorate-Granting II and Comprehensive I schools under the Carnegie Classification of 1987 were kept in the sample⁴.

Variables

Publication output in plant-biotechnology related sciences. The dependent variable of interest is the university's publication output that is relevant to industrial R&D in plant biotechnology. The easiest way to collect the data for this dependent variable is to gather all publications in journals that specifically focus on plant biotechnology. However, this comes at a cost of missing relevant articles that are published in journals of a broader discipline, such as Plant Physiology and Journal of Biological Chemistry. In order to gather all relevant articles

⁴ I used the 1987 Carnegie Classification as that is the oldest report that is available online (the first report was in 1973).

regardless of the journal' s disciplinary orientation, I use the following two-step procedure: I first downloaded titles and abstracts from the top three journals in the field of plant molecular biology and genetics: Plant Cell, Plant Molecular Biology and Plant Biotechnology Journal. By using a text-mining process⁵, I extracted a set of essential keywords that are relevant to sciences of plant biotechnology and repeatedly appear in these articles. Then I applied the combination of these keywords to search Web of Science to download all publications which contain the keywords in their title or abstract. Table 3 shows that plant biotechnology research appears across many journals, including non-plant biotechnology specific journals. I identified the author addresses in these articles to aggregate them at the university level.

Colocation with Industry R&D. As aforementioned in the previous section, I was able to identify as the loci of treatment the following five locations: Monsanto Headquarters in Creve Coeur, Missouri; Du Pont Experimental Station in Wilmington, Delaware; Ciba Geigy (now Syngenta)' s Agricultural Biotechnology Research Center in Research Triangle Park, North Carolina; Pioneer Hi-Bred (now part of Du Pont) Headquarters in Johnston, Iowa; DowElanco (now Dow Agrosciences) Headquarters in Indianapolis, Indiana. I identified the exact location of main R&D laboratory by cross-checking the Directory of American Research and Technology and the author addresses in company publications.

Universities that are within 100 mile radius of these locations are considered to be geographically proximate to the loci of industrial R&D (i.e. colocated with the company), as suggested in Furman and MacGarvie (2009). The treatment is considered to have taken place when the colocated company entered into plant biotechnology R&D by launching an official internal unit or a joint venture dedicated to plant biotechnology (e.g. Monsanto in 1981, Ciba Geigy in 1984, Pioneer in 1989, DowElanco in 1989). In the case of Du Pont, I could not date

⁵ I used the online text-mining tool called TerMine, available at <http://www.nactem.ac.uk/software/termine/>.

the official launching of a plant biotechnology team from official sources, although it is known that it entered the industry around the same time as Monsanto (Charles, 2001). Instead, I take 1982 as the treatment year, when Du Pont first published an academic paper in the topic of plant molecular genetics.

Strength of Boundary-spanning Institutions. My hypothesis states that the impact of industry R&D will affect a colocated university when its researchers have access to boundary-spanning institutions that facilitates and incentivizes university-academia interactions. Ideally, I would like to examine institutional, microfoundational features that can gauge a university's boundary-spanning capacity, such as whether the university has had a strong technology transfer office, or the extent to which the university values academic patenting or applied research publications in tenure judgment. Because of data constraints, I use two proxy measures for the strength of boundary-spanning institutions within a university: (1) stock of pre-1980 university patents and (2) the existence of medical school.

The fact that a university had been actively patenting before 1980, even prior to the enactment of Bayh-Dole Act which opened the era of academic patenting, suggests that the university must have had exceptionally strong culture and infrastructure that support research commercialization. Such universities are likely to have had high experience in technology transfer services and industry collaboration, which will further facilitate and incentivize academic scientists to span industry boundary. Having a medical school also has a similar implication, in that it is the earliest form of institutional innovation that incentivized practical, applied and technological research even before the advent of biotechnology (Rosenberg, 2009). By being an early pioneer in academic patenting (even prior to the Bayh-Dole Act) or having had a medical school, university must have built from the early exposure to technology transfer and

industry collaboration more systematic infrastructure to further aid subsequent industry boundary-spanning. Thus, the universities with higher initial boundary-spanning capacity will exhibit a faster subsequent development of boundary-spanning capacity and a faster shift into industry-relevant research compared into their counterparts.

I search the USPTO patent data to identify patents applied by universities up to the year 1980. The stock of patents should function as a proxy of institutional tendency to engage in applied and industry-relevant research and the experience gathered from prior interactions, rather a proxy of the capacity for biotechnology research in particular. Thus, I exclude all patents in class 435, 436, 530, 800 and 930, which are directly related to biotechnology. Then I code universities that are among the top 5% patentee (in terms of application) as high boundary-spanning.

University-level Controls. I use a set of university-level variables to match control universities to the set of treated universities. From the NSF Survey of Research and Development Expenditures at Universities and Colleges, I collected the university' s R&D expenditures separately funded by NIH, NSF and the USDA in each year. In cases which the R&D expenditure data was only available at the university system level (whereas the relevant unit of observation is its campus), I used the campus-level student body size to break it down. The information on general university characteristic such as Carnegie Code, land-grant status, the list of active departments and the size of the student body in each department was collected from the NSF Survey of Graduate Students and Postdoctorates in Science and Engineering (GSS survey).

Difference-in-Differences and Coarsened-exact Matching

The main empirical strategy of this study is difference-in-difference-in-differences(DDD) and coarsened exact matching. Universities that are colocated with the R&D headquarters of these firms are considered to be have been treated, after the colocated firm's entry into plant biotechnology. The impact of industry R&D on the treated universities will be compared against control universities which are comparable on observable characteristics. I identify the control universities by using coarsened exact matching (Iacus et al., 2012), an empirical approach which remedies the endogeneity of treatment variable by balancing the treated and control observations on exogenous variables.

I start the DDD estimation by first looking at the before-and-after change in publication outcome for the high boundary-capacity universities in the treated locations. I subtract from this estimate the average change in means for the control universities with high boundary-spanning universities and the change in means for the low boundary-spanning universities in the treated locations. By doing so, I can control for two confounding trends, namely the change in publication outcome of high boundary-spanning universities regardless of the treatment and the change in outcome that all treated universities will experience because of other location-specific issues.

The controls were chosen based upon the following set of covariates: the average R&D expenditure separately funded by NSF, USDA and NIH and the student body between 1971 (or other earliest year reported) and one year prior to the treatment, as well as whether the university already had an agricultural department prior to 1980. I coarsened the joint distribution of the covariates by breaking the continuous variables into separate bins and keeping the strata that contained one treated university and at least one control. I implement the CEM procedure before each treatment year (1981, 1982, 1984, 1989) without replacement, trimming the number of

observations from 500 to 280 universities. The number of control units to treated units varies from strata to strata. Because my CEM results in one-to-many (or many-to-many) match, each unit is given a weight so that a weight of 1 is assigned to each treated unit and Ti/Ci (number of treated observations in the strata/controls in the strata) to each control unit in the strata (Iacus et al., 2012).

My estimation equation is a triple-difference (DDD) model, which includes the necessary interaction effects to identify the difference between the impact of colocated industry R&D upon the universities with strong boundary-spanning capacity and the impact of industry R&D upon those without the strong boundary-spanning capacity.

$$Publication_{i,t} = f(\alpha_i + \beta_t + \gamma_i \times Coloc_i \times Post-Entry_{i,t} + \delta_i \times Boundary-Spanning_i \times Post-Entry_{i,t} + \mu \times Boundary-Spanning_i \times Post-Entry_{i,t} \times Coloc_i)$$

$Boundary-Spanning_i$ is a dummy variable coded as 1 if university i has strong boundary-spanning capacity prior to the treatment (if the university had a medical school, or if the university had been a top 5% patentee). $Coloc_i \times Post-Entry_{i,t}$ is a dummy variable that equals 1 for treated universities, only in those years after the company colocated with the treated university entered into plant biotechnology R&D. $Coloc_i \times Post-Entry_{i,t} \times Boundary-Spanning_i$ is a dummy variable that equals 1 for treated universities that have strong boundary-spanning capacity, only in those years after the company colocated with the treated university entered into plant biotechnology R&D. Interaction variables that are constant within observation (e.g. $Coloc_i \times Boundary-Spanning_i$) were not included in the equation as they were absorbed by university fixed effect α_i . β_t controls for year effect.

The coefficient δ_i we obtain from the regression can be interpreted as the change in outcome that treated universities without strong boundary-spanning capacity will experience.

can be interpreted as the change in outcome that control universities with strong boundary-spanning capacity will experience. Most importantly, the coefficient of interest μ captures the impact of local industrial R&D upon high-boundary spanning universities after netting out the effect of high boundary-spanning capacity upon universities in non-treated regions.

$$\mu = (\bar{y}_{\text{local, high-boundary-spanning, post}} - \bar{y}_{\text{local, high-boundary-spanning, pre}}) - (\bar{y}_{\text{non-local, high-boundary-spanning, post}} - \bar{y}_{\text{non-local, high-boundary-spanning, pre}}) - (\bar{y}_{\text{non-local, low-boundary-spanning, post}} - \bar{y}_{\text{non-local, low-boundary-spanning, pre}})$$

As for the estimation, I used the fixed-effect Poisson model with robust standard errors, clustered at the university level. The regression is weighted by the individual weights assigned in the CEM procedure.

ANALYSIS AND RESULTS

After trimming the original data from the GSS survey and matching it with university R&D expenditure data, I perform coarsened exact matching to pair treated universities to control universities. After dropping unmatched universities, my sample consists of 280 universities. The descriptive statistics of these universities are presented in Table 2, which confirms that my CEM procedure resulted in a balanced match of treated and controls, so that there is no significant difference between the sample moments of the two groups. Matching on the R&D expenditure funded by the public sources (NSF, NIH and USDA), student body and the agricultural sciences department seemed to have helped achieve a balance across most observable covariates.

Table 4 reports the fixed effect Poisson regression estimates of the impact of local industry R&D upon university's plant biotechnology-related publication outcome. The coefficients are reported in incident rate ratios, so that a value greater than 1 would mean a

relative increase. All models include university fixed effect and year effect, which control for the university's time-invariant unobservables that are correlated with the treatment status and may affect the publication outcome. Standard errors were clustered at the level of university. Because I use university fixed effect, time-invariant interaction variables (e.g. Colocation \times Medical) are dropped from the model.

The first column in Table 4, Model 1 explores the general temporal trend in the academic realm of plant biotechnology research. It shows that the increase in the plant biotechnology publication outcome has been driven by universities that have had a medical school, rather than universities that have had an agricultural sciences department. After the advent of the plant biotechnology industry, universities that have had a medical school published 70% more plant biotechnology articles compared to those without a medical school. Although not statistically significant at the level of $p=0.05$, universities that already had an agricultural sciences department school before 1980 published 33% less plant biotechnology articles compared to previously non-agricultural universities.

This shows that plant biotechnology research requires a totally different academic background from traditional agricultural research. The result chimes with the historical fact that the technological discontinuity was driven by the non-land grant, non-agriculture-focused universities that had expertise in basic molecular biology (Kenney, 1986).

Having a greater scientific capability in general, as proxied by the logged amount of average NSF funding prior to 1980, did not have a significant impact upon plant biotechnology publication outcome. Neither does being the top 5% academic patentee before 1980, which is the proxy of a university's strong boundary-spanning capacity, significantly increases the plant biotechnology publication outcome. This shows that plant biotechnology research in the

academic realm was not particularly driven by the most research-intensive universities nor the highest-patenting universities on average.

Without controlling for the time-varying trend of different universities, Model 2 reports that the treated universities that were in the geographical proximity of industrial R&D are shown to have published 36% less plant biotechnology publication compared to the controls, as shown in Model 2. However, significance of the negative coefficient disappears in Model 3, after controlling for the time-varying effect of other pre-treatment university characteristics.

In Model 4, I saturate the model by interacting all pre-treatment variables with colocation. The purpose of this model is to explore whether time-varying effects of pre-treatment university characteristics vary between the treated and control universities. The special focus is on identifying differential effect of treatment for the treated universities with high boundary-spanning capacity, which will be equivalent to μ in the equation above.

Model 4 supports my hypothesis that the impact of local industrial R&D is positive only among universities with stronger boundary-spanning capacity. As predicted, the coefficient of Post-Entry*Colocation*(Pre-1980) Top Patentee and Post-Entry*Colocation*Medical are positive and significant. This confirms that being a top patentee or having a medical school makes a local university respond stronger to industrial R&D. Colocated universities with a medical school experience a 17% boost in plant biotechnology publications, compared to colocated universities without a medical school after controlling for the increase in publication outcome experienced by the control universities without a medical school. The effect of local industrial R&D is even greater for universities which were top 5% academic patentees before 1980. Treated universities which had been the top 5% patentee experienced a 140% boost in the publication outcome, compared to other treated universities with less prior patents.

The coefficient on PostEntry*Coloc*Pre-1980 Ag. Dept and PostEntry*Coloc*Pre-1980 NSF (log of NSF fundng) are both negative and insignificant, showing that having an agricultural department or higher scientific capability in general did not particularly act as an advantage for the colocated universities. In other words, this implies that boundary-spanning capacity has a distinct implication about the university' s response to local industrial R&D, compared to research expertise in general.

Of course, although medical school and prior patenting are interpreted as a proxy of stronger boundary spanning institutions, they are also correlated with the university' s research capacity in applied sciences. This concern is alleviated because the time-varying effect of prior research strength is separately controlled in the model, proxied by the mount of NSF funding received previous to the treatment.

Interestingly, top 5% patentees that are not located within geographical proximity of agricultural anchor tenants exhibit a relative decrease in plant biotechnology publication. The results show that the plant biotechnology publications of *control* (non-colocated) universities which had been among the top 5% patentees (before 1980) experienced a 36% decrease, compared to other control universities with less prior patents. High boundary-spanning universities located in other innovation systems may be focused on catering to the needs of their own local industry that is non-agricultural, and this may crowd out the agricultural research.

As a word of note, I intentionally choose not to include time-varying control variables at the university level, such as the number of student body or the amount of government research funding in the focal year. This is because most of these time-varying variables can be an endogenous outcome of treatment (“bad control” problem as described in (Angrist and Pischke, 2008)). For example, if local industrial R&D were to increase the university' s research

productivity, this will increase the government research funding as well as the number of students applying to the university. In unreported regressions, I try including the log of yearly NIH funding as time-varying control variable, assuming that including the trend in pharmaceutical-oriented research output may control for non-plant biotechnology shocks. This does not change the regression in any meaningful way.

Overall, the findings suggest that the impact of local industrial R&D has a greater positive impact upon universities with strong boundary-spanning capacity. This supports my argument that university' s response to local industrial R&D depends upon whether the university has an institutional system that incentivizes and facilitates its researchers to span the industry boundary and reap the pecuniary returns.

DISCUSSION AND CONCLUSION

This study explores the impact of local industrial R&D upon the publication outcome of universities in the industry-relevant fields of science. By using the entry of agricultural anchor tenant firms into plant biotechnology as the treatment upon nearby universities, I find evidence that a university' s response to local industrial R&D hinges upon its boundary-spanning capacity which incentivizes and facilitate its researchers to engage in industry interactions. In order to alleviate the endogeneity of industrial R&D location to university research, I leverage the fact that the location of agricultural anchor firms had been predetermined prior the rise of biotechnology research and been maintained due to the locational inertia. I also control for the confounding effect by matching treated universities to the control universities that are comparable in pre-treatment observables that can affect the publication outcome. The regression

results confirm my conjecture that local industrial R&D has a greater positive effect upon universities with high boundary-spanning capacity.

I believe that this paper makes the following contributions to the literature on economics of science and innovation. First, this study adds to the empirical studies which explore the endogeneity of academic science to industrial and socioeconomic environment. Whereas the prior literature emphasized the contribution of academic knowledge to industrial innovation and technology, what shapes the direction of academic research has been an understudied topic. Previous studies have focused on the role of academic patenting and shown that entry into the patenting regime skews academic research towards more patentable research. Instead of focusing on patentability of academic research at the general level, I show that industrial R&D can skew academic research towards particular areas of sciences that the industry depends on. To my knowledge, although the co-evolution of industrial sector and academic discipline has been examined through case studies and descriptive statistics (Murmann, 2013), few studies have quantitatively identified the causality that underlies the convergence between industrial R&D and academic research. In addition to avoiding the reverse causality by focusing on the unique setting of agricultural biotechnology where the locations of R&D had been pre-determined by locational inertia, I also try to isolate the impact of treatment from other confounding factors by using difference-in-differences, coarsened exact matching and fixed effects.

Second, this study makes a contribution to the literature of regional innovation system and localized externalities by showing that the co-evolution of industry and academia within a regional innovation system is intermediated by institutional infrastructure and incentives. The finding that the impact of local industrial R&D upon universities is moderated by boundary-spanning capacity implies that the rate and direction of academic research hinges upon

institutional norms and incentives. This has implications for both policy practitioners and industry participants who want to foster active synergy between local industry and academia. The example of how institutional norms can act against the local industrial R&D is Princeton University, a top-tier research university located in the geographic proximity of the historical New Jersey pharmaceutical and medical technology cluster. If industry colocation by itself were to shape the direction of academic research, one would expect to see Princeton University having a competent medical school and highly productive in pharmacology, medicinal chemistry and medical engineering by now. However, such change had been blocked by Princeton's historical identity and practices as a guardian of pure research without any professional school. This implies that strong scientific capability is not a sufficient condition for the convergence between local industry and academia. Norms, incentives and culture matter.

Third, this study has implications for the study of university as a hybrid organization, which needs to maintain multiple and occasionally incompatible institutional logics (Murray, 2010). While previous literature has explored how hybrid organizations can address the conflict among multiple logics, less scholarly attention has been paid to why some hybrid organizations embrace multiple logics together, whereas others persistently favor one logic over another (Battilana and Dorado, 2010). My finding implies that the embracement of a new logic is a path-dependent process which is bounded by the organization's prior experiences and norms.

At this stage, this study leaves room for further research and refinement. First, we should delve deeper into the actual micro-mechanisms that motivate the academic researchers to consider industry-relevant fields of science as their topic. I discussed in my hypothesis development a number of possible mechanisms such as increased industry funding, job

opportunity and entrepreneurial motivation. It would be meaning to understand which mechanism has a meaningful effect and its magnitude.

Second, although I tried my best to avoid the endogeneity concerns, the result can still be confounded with other locational-specific shocks that selectively affected traditional locations. This can happen for example if the government in Missouri, North Carolina, Iowa, Indiana and Delaware had been selectively more active since the early 1980s in supporting plant biotechnology research, compared to other regions. In an unreported regression, I do not find that land-grant universities in these areas perform better than land-grant universities in other areas (actually worse).

Although the impact of industrial R&D does have a positive impact upon academic research towards industry-relevant orientation, whether it comes at a cost of other research is a separate issue. I hesitate to make any overall welfare judgment about the impact of industrial R&D from this study. However, this study carries an implication from the policy practitioners that are trying to promote a university-based industry cluster. Although investing in universities for better scientific research capability is itself an important policy for the well-being of an innovative cluster, cluster policy practitioners need to enhance the university's institutional infrastructure, incentives and norms so that the research capacity is better aligned to the local industry and thus be able to be put to a productive use from the industry perspective.

Table 1. Plant-Related Agricultural Biotechnology Patent Grant By Assignees (1976-2000)

First Assignee (location)	Number of Agbio Patents	%	Cumulative %
PIONEER HI-BRED INTERNATIONAL, INC. (Des Moines, IA US)	441	5.43	5.43
MONSANTO CO., INC. (St. Louis, MO US)	256	3.15	8.58
U.S. DEPARTMENT OF AGRICULTURE (Washington, DC US)	185	2.28	10.86
MYCOGEN PLANT SCIENCE, INC. (San Diego, CA US)	154	1.9	12.75
BAYER AG (Leverkusen, DE)	133	1.64	14.39
UNIVERSITY OF CALIFORNIA (Oakland, CA US)	131	1.61	16
HOECHST JAPAN LTD. (Frankfurt, DE)	123	1.51	17.52
DEKALB GENETICS CORP. (DeKalb, IL US)	112	1.38	18.89
NOVARTIS AG (Basel, CH)	106	1.3	20.2
ASGROW SEED CO. (Kalamazoo, MI US)	90	1.11	21.31
AJINOMOTO CO. INC. (Tokyo, JP)	80	0.98	22.29
DU PONT, E.I. DE NEMOURS AND CO. (Wilmington, DE US)	80	0.98	23.28
AMERICAN CYANAMID CO. (Madison, NJ US)	79	0.97	24.25
BASF AG (Ludwigshafen, DE)	78	0.96	25.21
ZENECA LTD. (London, UK)	77	0.95	26.16
WISCONSIN ALUMNI RESEARCH FOUNDATION (Madison, WI US)	76	0.94	27.09
CORNELL UNIVERSITY (Ithaca, NY US)	74	0.91	28
ELI LILLY AND CO. (Indianapolis, IN US)	74	0.91	28.91
CALGENE L.L.C. (Davis, CA US)	73	0.9	29.81
CIBA-GEIGY AG (Ardsley, NY US)	70	0.86	30.67
MICHIGAN STATE UNIVERSITY (East Lansing, MI US)	70	0.86	31.54
NEW ENGLAND BIOLABS, INC. (Beverly, MA US)	70	0.86	32.4
Total	8,124	100	100

Source: USDA Agricultural Biotechnology Patent Data

Note: Focal firms of treatment highlighted in boldface

Table 2. T-Test of Treated Universities and Control Universities' Pre-Treatment Characteristics

	Treated Universities	Control Universities	Difference	T-stat (P -value)
PB Publication Count	0.40 (0.18)	0.15 (0.05)	0.24(0.18)	1.33(0.184)
Patent Count	0.81(0.35)	0.80(0.19)	0.01(0.40)	0.01(0.989)
Land-grant	0.14(0.04)	0.11(0.03)	0.03(0.06)	0.60(0.549)
Medical	0.25(0.05)	0.25(0.06)	0.00(0.08)	0.05(0.957)
Public	0.62(0.06)	0.55(0.09)	0.07(0.11)	0.69(0.493)
Student Body	576.9(108.4)	576.7(90.3)	0.14(141)	0.00(0.999)
USDA funding	691.1(295.5)	666.9(242.7)	24.19(382)	0.06(0.950)
NSF funding	995.46(245.76)	1073.35(286.98)	-77.9(377.8)	-0.21(0.837)
NIH funding	3667.2(1513.5)	3797.4(1241.8)	-130.17(1958)	-0.07(0.947)
Agri. Dept.	0.13(0.04)	0.19(0.05)	-0.06(0.06)	-0.99(0.324)
Botany Dept.	0.19(0.05)	0.15(0.04)	0.04(0.06)	0.69(0.493)
Genetic Dept.	0.21(0.05)	0.15(0.05)	0.06(0.07)	0.78(0.436)
	48 universities	232 universities		

Note: Weighted mean (SD) reported. CEM covariates in bold.

Table 3. Top 15 Journal Outlets for Plant Biotechnology-related Research

Journal Name	Count	%
PLANT PHYSIOLOGY	6,338	6.88
CROP SCIENCE	4,571	4.97
PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES	4,040	4.39
PLANT CELL	3,675	3.99
THEORETICAL AND APPLIED GENETICS	3,501	3.8
PLANT JOURNAL	2,977	3.23
PLANT MOLECULAR BIOLOGY	2,534	2.75
GENETICS	2,410	2.62
PHYTOPATHOLOGY	1,761	1.91
MOLECULAR PLANT-MICROBE INTERACTIONS	1,624	1.76
JOURNAL OF BIOLOGICAL CHEMISTRY	1,536	1.67
PLANT DISEASE	1,375	1.49
GENOME	1,228	1.33
Total	92,060	

Table 4. Fixed Effect Poisson Regression of Plant Biotechnology Publications between 1972-2009

	Model (1)	Model (2)	Model (3)	Model (4)
	Baseline Time- Varying	Colocation Only	Colocation + Time- Varying	Coloc. × Time- Varying
		0.642**	0.815	1.826
PostEntry*Coloc		(0.107)	(0.165)	(1.096)
PostEntry* Pre-1980 Ag. Dept	0.676 (0.139)		0.674 (0.148)	0.600** (0.110)
PostEntry*Coloc* Pre-1980 Ag. Dept				0.999 (0.373)
PostEntry* Pre-1980 NSF	0.999 (0.0297)		1.010 (0.0379)	1.035 (0.0277)
PostEntry*Coloc* Pre-1980 NSF				0.879 (0.0703)
PostEntry* Pre-1980 Medical	1.715*** (0.215)		1.562*** (0.154)	1.547*** (0.122)
<i>PostEntry*Coloc* Pre-1980 Medical</i>				1.174* (0.382)
PostEntry* Pre-1980 Top Patentee	0.954 (0.162)		1.038 (0.235)	0.640*** (0.0801)
<i>PostEntry*Coloc* Pre-1980 Top Patentee</i>				2.408*** (0.602)
Univ. FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Observation	7942	7942	7942	7942
Group	209	209	209	209

Notes: Robust (QML) standard errors clustered by the university. Exponentiated Coefficients (IRR).

* p<0.05, ** p<0.01, *** p<0.001

Table 5. Correlation Matrix

	Mean	S.D.	Min	Max	pcount	coloc	nsf_pre80	usda_pre80	nih_pre80	agsci_pre80	medical	patent_pre80
pcount	2.73	10.61	0	143	1							
coloc	0.12	0.33	0	1	0.05	1						
nsf_pre80	1204.49	3009.07	0	26952	0.34	-0.01	1					
usda_pre80	761.14	2195.67	0	14251	0.53	0	0.28	1				
nih_pre80	3252.06	7974.27	0	44327.5	0.25	0.06	0.67	0.11	1			
agsci_pre80	0.22	0.41	0	1	0.37	0.04	0.21	0.63	0.12	1		
medical	0.24	0.43	0	1	0.18	0.06	0.35	0.14	0.61	0.1	1	
patent_pre80	8.3	30.54	0	295	0.22	0.04	0.53	0.06	0.38	0.04	0.14	1

Variables Description

pcount	The number of plant biotechnology articles published in a year by the focal university
colocation	1 if the focal university is located within 100 mile radius of industrial R&D laboratory, 0 otherwise
nsf_pre80	Annual average of NSF research funding that the focal university received prior to 1980
usda_pre80	Annual average of USDA research funding that the focal university received prior to 1980
nih_pre80	Annual average of NIH research funding that the focal university received prior to 1980
agsci_pre80	=1 if the focal university had an agricultural sciences department prior to 1980, 0 otherwise
medical	=1 if the focal university had a medical school prior to 1980
patent_pre80	The stock of patents that the focal university had applied for up to 1980

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