Academic Knowledge Spillovers and the Role of Geographic Proximity in Regional Agriculture-related Sectors: The impact of agricultural research at Colorado State University on the Colorado economy, and beyond

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Abstract

This study examines the mechanisms and geographic scope of the impact of university knowledge spillovers on the agricultural economy, using the case of Colorado State University (CSU) and the state's agricultural economy. Our findings show that the spillover impacts of journal publications are rarely localized within Colorado; rather, the geographic scope of these impacts is national and even global. However, the extent to which the spillover impacts of patented knowledge is localized within Colorado is open to question because it is possible to control permissions for use, but at the same time it is impossible to limit everyone's awareness and use of it, particularly in foreign jurisdictions where patents are not taken out by the university. The collaboration mechanism of knowledge dissemination, such as indicated by industry coauthorship on journal articles and private sponsorship of grants and contracts, which are more rivalrous by virtue of the more tacit qualities of knowledge being disseminated and because of the higher transaction costs, requires closer interaction and greater geographic proximity, which usually prevents global dissemination. Thus, we observe geographic proximity is significantly important for these channels. Finally, university start-ups are highly geographically bounded near universities because in the early stages start-up companies need support from their host university.

Keywords: knowledge spillovers, geographic proximity, innovation, agriculture, university research, non-parametric model

JEL Classifications: Q16, R12, O33, D23, C14

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I. Introduction

Technology or knowledge spillovers are one of the most important sources of externality benefits in our society and economy. Defined as spreading into another area, knowledge spillovers are an important issue for economic development, underlying many of our commonly held assumptions about commercial innovation processes. Moreover, historically, knowledge was understood by most economists to have purely public-good attributes, but more recently, the characteristics of knowledge have come to be viewed as more various, with different degrees of appropriability, due to differences in tacitness, embeddedness, or legal excludability because of well-developed intellectual property rights. In industry, knowledge is one of the most important assets today. Firms protect their knowledge or technology by various types of intellectual property and contractual mechanisms, including patenting and licensing. Therefore, questions of knowledge spillovers in industrial or commercial innovation have been analyzed extensively by many researchers (Jaffe, 1989; Mansfield, 1991 & 1995; Henderson et al, 1998; Jensen and Thursby, 2001; Adams, 2002; Cohen et al, 2002; Shane, 2002; Thursby and Thursby, 2011) and are important to both industry leaders and policymakers.

In high-tech industries, such as biotechnology and semi-conductors, spillovers of technology among similar firms are quite quickly transmitted and improved upon by rivals' follow-on inventions and innovation. Moreover, in technologically advanced countries, such as the United States, Japan, United Kingdom, Germany, France, and Israel, there is an ongoing exchange of people and ideas among private firms, universities, and research institutes located in close proximity to one another (Krugman and Wells, 2013). Positive externalities can increase the incentives for cooperative research and development (R&D) between universities and industries, and are a fundamental reason that the government supports the costs of R&D.

In both the industrial economy and the post-industrial knowledge economy, one of the major sources of technology spillovers have been universities and research institutes. Following Mansfield (1991 & 1995) and Henderson, Jaffe, & Trajtenberg (1998), we know that a range of new industrial products and processes are based on academic research, and some industries--such as electrical equipment, instruments, chemicals, drugs, mining, and petroleum--would not have developed in the way they did without recent academic research. University knowledge production activities have the potential both to directly affect commercial innovation and indirectly affect economic growth and development.

Most research universities in the United States are independent non-profit or state-affiliated knowledge organizations. They perform not only an educational function, but they also create and disseminate new knowledge through their other core functions as well. The roles and missions of universities have been shaped by a long history of national government policy changes, such as the Morrill Land-Grant Act of 1862, the Hatch Act of 1887, the Smith-Lever Act of 1914, and the Bayh-Dole Act of 1980. Following these formative policy changes, the universities in the United States have generally come to embrace three missions: an educational mission, a research mission, and an outreach mission. These different missions have spurred the emergence of different types of knowledge dissemination channels used in universities, such as the public domain, tacit dissemination through close collaboration, patenting/licensing of inventions and technical knowledge, and venture creation. These encompass not only traditional modes of university knowledge dissemination, such as publications, conference presentations, collaborative research with industry partners, consulting, co-supervising internships, and so on, but also newer modes of university knowledge dissemination, such as university invention disclosures, patenting/licensing, and new tech venture startups. In agriculture, the Land Grant universities have long focused on agricultural research and the commercial dissemination of university innovations for regional and state economic growth as well as national and even international development.

The main purpose of this study is to examine the geospatial pattern of Colorado State University (CSU) knowledge spillovers and its commercial economic impact, especially within Colorado's agriculturally-related sectors or industries, but also nationally and globally. In particular this study seeks to identify how different channels of knowledge dissemination from the university differ in the type and location of impact on commercial efforts at innovation within the agricultural value chain, regionally, nationally, and even globally? What is the relationship between geographic distance (proximity) and the types of university knowledge transfer mechanisms used? Can we differentiate between knowledge dissemination channels specialized in disseminating 'sticky' (tacit) versus 'slippery' (codified) knowledge? We expect different university knowledge dissemination channels to be specialized in disseminating sticky or slippery (tacit or codified) forms of knowledge, with the former staying within the local or regional economy and the latter types more readily spilling over nationally or even globally.

The rest of this study is consisted of into four sections. Section II reviews and discusses previous studies of knowledge spillovers and geographic proximity. Section III provides information on the structure of the agricultural economy and the industry value chain within Colorado. Section IV shows the empirical study of university knowledge spillover across the different dissemination channels. Finally, Section V summarizes the main conclusions.

II. Geographic Proximity and University Spillovers

Active interaction between university researchers and industry is important for dissemination of some types of knowledge, and because of that the geographic location of impact is arguably influenced by the characteristics of the knowledge being disseminated. When it comes to considering the importance of university knowledge transfer activities and their impact on industrial innovation and invention, geographic proximity has become a significantly more important factor to both academic researchers and private entities (Jaffe, 1989; Mansfield, 1991 and 1995; Lee, 1996; Henderson et al, 1998; Paytas, 2004; Laursen and Salter, 2004; Audretsch and Lehmann, 2005). However, this is not always true; less geographic distance does not always effectively lead to higher commercialization outcomes, and in some cases, such as a central government system, and the problem of lock-in, meaning a lack of openness and flexibility, geographic proximity can even be an obstruction to achieving university-industry collaboration (Herrigel, 1993; Boschma, 2005; Hong and Su, 2013; Buenstorf and Schacht, 2013). Nevertheless, a university's research and knowledge dissemination activities still play a significant role in providing knowledge inputs to industry innovation and inventions within its region, at least in particular fields and technologies (Anselin et al, 1997 and 2000).

According to Adams (2002), the localization of university spillovers is higher than industrial spillovers, and the degree of localizations depends on the nearby stocks of R&D, but the degree is decreased by the size of firm and laboratory. Moreover, this study suggests that the results on localized university spillovers reflects the dissemination of normal science and the industry-university cooperative movement, so the geographic localization occurs simultaneously with the public good attributes of academic research. Similarly, Ponds et al (2009) find that university spillovers can be localized by geographically bounded mechanisms, but university-industry collaborations are not limited to the regional scale. Their findings shows that university research impacts local innovation and inventions not only due to geographic proximity, but also due to collaboration networks.

Evaluating both the public and the private benefits of university knowledge spillovers relies considerably on the different types of knowledge dissemination. According to Jaffe (1989), when the channel is published journal articles, then geographic proximity is unimportant, but when the channel is informal interaction, then geographic locations is important in capturing the benefits of spillovers. In looking at patent citations, Jaffe et al (1993) find that inventors are more likely to cite patents from the same country, state, and even the same metro area and thus the geographic location of the knowledge spillover is localized. With regard to collaboration between university and local industry, this type of knowledge dissemination is highly concentrated within geographical boundaries. According to Lester (2004), university contributions to regional commercial innovation processes can be achieved in various ways. Many universities are searching to develop their discoveries and findings by patenting and licensing to local companies, yet the most important contribution of the university may be through education and informal interactions as a public service to local communities and businesses.

III. The Regional Agricultural Economy and Value Chains

The state economy of Colorado had long depended on agriculture and innovation as drivers of economic growth and development. In 2011, the supply of agricultural inputs by Colorado agribusinesses contributed $2 billion, crop and livestock sales contributed more than $8 billion, and commodity marketing, processing, and food/beverage manufacturing contributed $15 billion to the state economy (Graff et al, 2013). Also in the one year of 2011, in agriculturally related fields[3], CSU researchers received $5.03 million in grant and contract awards from businesses in or closely related to agriculture, co-authored 24 scientific articles with ag industry partners, made 22 invention disclosures, submitted 11 patent applications , and founded one new startup company, again all involving technologies related to agriculture.

Colorado has a diverse agriculture and food sector, and several subsectors play important roles in the state economy. Colorado State University, as the Land Grant university in Colorado and a world leader in agricultural sciences, has had economic impact on these subsectors. Colorado is a major producer of beef and dairy, at both the farm level and in processing and manufacturing. Colorado State University has leading programs in veterinary medicine and animal science with emphases on large animal and bovine. Colorado is the 5th largest producer of potatoes in U.S., and CSU's Potato Breeding Selection Program has developed more than 60 percent of the potato varieties that are planted in Colorado. Colorado is a major wheat producing state and is home to the largest wheat milling company in the U.S., and the Colorado Wheat Breeding and Genetics program at CSU has improved more than 30 percent of wheat varieties grown in Colorado (CSU Ventures' Annual Report, 2012). Colorado maintains a good reputation for organic and natural foods. And Colorado hosts not only the two top brewing companies in the nation, but is also known for the high quality of local brewing firms[4].

According to Graff et al (2014), an innovation cluster in the agricultural and food industries appears to be forming in the Colorado Front Range. Innovation clusters can be defined as the

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[3] In that year, the range of research fields were included in animal health, dairy (organic milk), pest control, crop varieties, soil fertilizer, ground water & irrigation, and food processing & packing.

[4] Source: Colorado Office of Economic Development & International Trade. www.advancecolorado.com

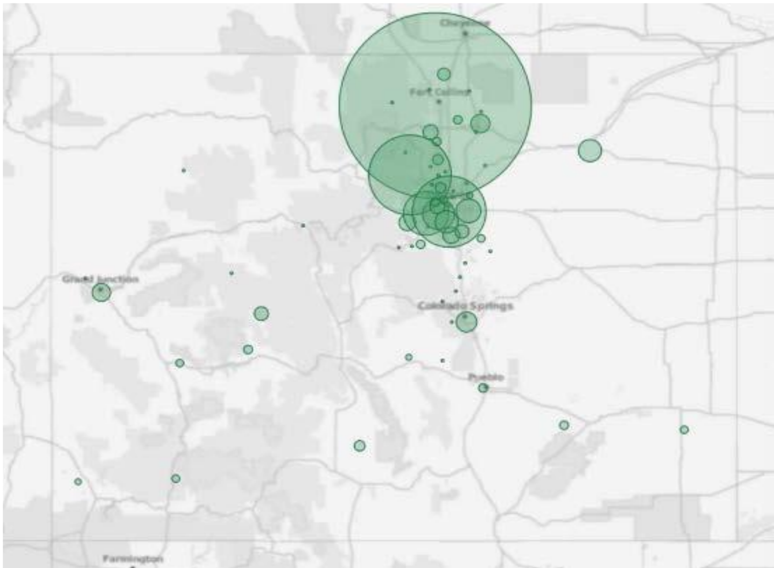
geographically proximate sets of interconnected companies and associated institutions in particular fields and technologies. The structure of the value chain of Colorado's agriculture and food industries is highly associated with the emerging innovation cluster. The agricultural value chain in Colorado includes 550 innovators, of which 460 are private-sector companies and 90 are public-sector (academic, nonprofit, and government) organizations, and the innovating organizations are categorized according to a dozen areas corresponding to different subsections of the value chain. Table 1 displays these areas of agricultural innovation going on in Colorado, and Figure 1 shows the geographic landscape of Colorado's agricultural innovation.

Table 1—The numbers of actively innovating private companies within Colorado's agricultural and food value chain in 2014, congregated into technological categories, with cumulative Web of Science (WoS) publications and U.S. patents in each category from 1990 to 2013.

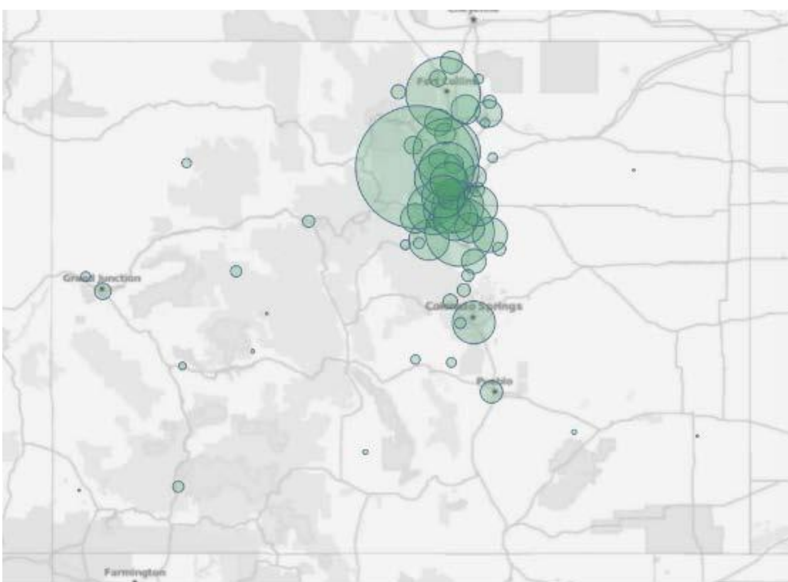
Technology	No. of company	No. of WoS publications	No. of U.S. patents
1. Water technology, infrastructure, analytics, and management	93	488	94
2. Soil fertility and pest control	23	21	68
3. Plant genetics and new crop varieties	20	30	527
4. Animal health, nutrition, and herd management	49	339	329
5. Agricultural information systems	22	3	97
6. Sensors, testing, and analytics for product quality and biosafety	32	119	99
7. Bio-energy & fuel	25	7	250
8. Commodity processing and food manufacturing	38	50	514
9. Dairy production and dairy product manufacturing	12	14	88
10. Beer, wine, & spirits production and marketing	67	26	37
11. Natural, organic, and local foods and marketing	33	7	36
12. "Fast & Fresh" food service	13	0	0
13. Other emergent subsectors	33	5	74
Total	460	1109	2,213

Source: Graff, Berklund, and Rennels, 2014.

Figure 1—A landscape analysis mapping two agricultural R&D outputs: scientific journal publications and U.S. patents filled and granted, from 1990 to 2013



A. Scientific journal publications in agricultural and food related fields, by city of author's institutional affiliation



B. U.S. patents on agricultural and food related technologies filled and granted by city of inventor's residence

Source: Graff, Berklund, and Rennels, 2014.

The two most active areas in Colorado in terms of scientific research are water and animal agriculture (Table 1). Water related companies in Colorado are highly involved in scientific research papers and engage in projects for water storage, transmission, and irrigation infrastructure.

Many of these companies consist of consulting and analytics firms or civil engineering firms. Moreover, the companies associated with animal health and nutrition—such as beef, dairy cattle, horses and sheep—participate actively in R&D for improving the quality of animal health and nutrition and herd management. Furthermore, as shown in Figure 1, the geographical locations of Colorado authors in the agricultural value chain are highly concentrated in Northern Colorado, between Denver, the main urban center, and Fort Collins, where CSU is located.

In addition, over the 5 years, 2008-2012, the College of Veterinary Medicine and Biomedical Sciences at CSU was top ranked in terms of privately sponsored grant awards and contracts, at an average of $5.8 million per year, and industry co-authored journal articles comprised an average of 75.6 articles per year. Moreover, the College of Engineering was second ranked over that time period, and the Department of Civil and Environment Engineering, which is the center of CSU's water related research, received private sector grants averaging $1.2 million per year, and published an average of 12.8 articles per year with industry co-authors.

From this evidence, we might expect that the roles and missions of land-grant universities are crucially important for the local commercial innovation and inventions in the agricultural value chain, as well as the importance of geographical proximity.

IV. Empirical Study of University Knowledge Spillovers in Agriculture

We seek to take into consideration the full range of potential knowledge dissemination channels, as indicated by such measures as academic journal publications, industry co-authorship on journal publications, private sponsorship of research grants and contracts, patent applications and granted patents, and startup companies, all from data collected at the level of the different research units of Colorado State University (CSU), from 1989 to 2012. These various measures make it possible to analyze the extent to which the different types of knowledge dissemination channels work. Four general types of knowledge channels are included in (1) the public domain channel, (2) the collaboration channel, (3) the intellectual property rights and licensing contracts channel, and (4) the venture creation channel.

Figure 2—The concept of four different types of university knowledge dissemination channels

	Non-Rivalrous (“Slippery” information, lower transaction costs, lower capacity requirements)	**Rivalrous** (“Sticky” information, higher transaction costs, higher capacity requirements)
Non-excludable	**Release via Public Domain**	**Collaboration**
Invoked exclusion	**Patenting/Licensing**	**Venture Creation**

The concept of multiple knowledge channels in this study can be understood as informed by Samuelson’s (1954) classic comparison of excludability and rivalry dimensions in “*The Pure Theory of Public Expenditure.”* As such, four different types of knowledge channels are introduced (see Figure 2). First, what we call the “public domain mechanism” of knowledge dissemination is most appropriate for those outputs of research that have the strongest public good attributes, defined as non-excludable and non-rivalrous. Thus, it is impossible to exclude anyone from accessing this knowledge and to prevent simultaneous use or access, which means full freedom of use and open access. Second, the "collaboration mechanism" of knowledge dissemination is defined as a common good that is non-excludable and, yet, more rivalrous, due to the tacit or "sticky" nature of the knowledge, with it skills or routines, thus preventing global dissemination via publication or even making simultaneous contact or contract with multiple parties less than effective. Dissemination or transfer of the knowledge requires close interaction, such as apprenticeship or collaboration. Third, the utilization of the intellectual property rights and contracts characterize the "patenting/licensing mechanism" of knowledge transfer, which is best suited when a certain degree of excludability is required to create sufficient incentives for follow-on investment in an otherwise non-excludable and non-rivalrous knowledge output. Thus, by virtue of the IP and contracts, it is possible to exclude others from accessing and making use of it. Finally, the "venture creation mechanism" of knowledge dissemination is best for raising private investment in the further development of knowledge treating it most like a private good, by virtue of IP making it relatively excludable and, by virtue of its intrinsic stickiness or context dependence, being relatively non-rivalrous, so it is possible to exclude others from accessing this knowledge and making simultaneous use of it.

In this study, we want to examine CSU's knowledge dissemination and its impact on commercial innovation within the state economy, specifically in sectors related to agricultural industry, in terms of the four different types of knowledge dissemination channels. Moreover, this study attempts to determine the locations of private industry innovators impacted by or associated with CSU agricultural research in both agricultural and related sectors, to confirm the relationship between geographic distance and the types of CSU knowledge transfer mechanisms employed. In agriculture and food-related research and activity, the four different types of knowledge channels are measured using the citations a sample of CSU journal publications, privately sponsored grants awards and industry co-authorship on articles, citations of CSU patent applications and granted patents, and CSU startups.

Table 2—Summary of data used to measure four different types of agriculture and food-related knowledge dissemination channels

Ag. Related CSU Knowledge Channels	Years	Sum
1. Public Domain Channel		
Published journal articles	2008-2010	1,202
Citations of these published journal articles	2008-2012	6,883
2. Collaboration Channel		
Privately sponsored grant awards and contracts	1989-2012	543
Total amount of the private grant awards (million $)	1989-2012	17.58
Industry co-authored journal articles	1989-2012	290
3. Patenting/Licensing Channel		
Patent applications and granted patents	1990-2013	76
Citations of these patents (Excluding self-cites)	1990-2013	1,868
4. Venture Creation Channel		
CSU affiliated startups	1989-2012	11

Table 2 provides summary statistics of the data used to measure activity in four different types of knowledge dissemination channels for CSU's agriculture and food-related research activities. First, within the context of agriculture (using Web of Science keywords, including agriculture, agronomy, entomology, food science, horticulture, plant sciences, soil science, veterinary science, and water) we select a target sample of 1,202 journal publications by CSU authors from the Web of Science database, published from 2008 to 2010. Using the Web of Science forward citations reporting tool, we find these 1,202 CSU articles have been cited 6,883 times, collecting from 2008 to 2012. We then analyze the location of the authors and other characteristics of these citing papers to understand the geographic footprint and the nature of spillovers via the public domain channel.

Second, from 1989 to 2012, 543 grant and contract awards were received by CSU from private sector sponsors to conduct agriculturally related research. The total amount of these awards was $37.68 million, and came from 169 private companies engaged in some aspect of agriculture or food related business.. CSU researchers have collaborated with and co-authored 290 agriculture and food-related journal publications with authors from 194 private companies from 1989 to 2012. We then analyze the locations and characteristics of these companies that awarded grants and contracts to CSU and the companies that co-authored with CSU to understand the geographic footprint and the nature of spillovers via the research collaboration channel.

Third, CSU inventors had 76 agriculture and food-related patent applications and granted patents from 1990 to 2013. By 2015, all of these patent applications and grants had received 1,868 forward citations from other patents, owned by 206 companies. We then analyze the location of the inventors and the assignee firms of these citing patents to understand the geographic footprint and the nature of spillovers that occur via the intellectual property licensing channel.

Finally, 11 startup companies were created from 1989 to 2012 from research in CSU's departments and research units around technologies associated with agriculture. We analyze the locations and characteristics of these startup companies to understand the geographic footprint and the nature of spillovers via the venture creation channel.

Across these four different types of knowledge dissemination channels, this section seeks to determine the locations of private industry innovators in agricultural sectors that utilize the university's knowledge outputs, to ascertain the relationship between geographic distance and the type of channel employed. We expect the different channels to specialize in disseminating sticky or slippery (tacit or codified) forms of knowledge in agriculturally related sectors, some staying within the Colorado and other spilling over more readily nationally or even globally.

A. Geographic footprint of university knowledge spillovers

1. Public domain mechanism of knowledge dissemination

Journal publications are the major research output of universities, and this channel has the strongest public good attributes, defined as non-excludable and non-rivalrous. Once published (and if not otherwise protected, such as by a patent), it is impossible to exclude anyone from accessing this knowledge or to prevent simultaneous use or access, which means full freedom of use and open access. Again, according to Jaffe (1989), when the mechanism of dissemination is primarily journal publications, then geographic location is generally unimportant for recipients to access the benefits of knowledge transfers. Journal publications are the channel most likely to be used to transfer “slippery” information, that which is relatively codifiable and transmissible at lower transaction costs, so that the boundary of the knowledge spillovers is effectively worldwide, and it has the highest speed of transmissions and spillovers.

Table 3 shows the numbers of articles citing CSU’s agriculture-related journal publications within the target sample created using seven Web of Science’s categories for disciplines encompassing the whole agricultural value chain. In Table 3, the number of citing articles by authors in other countries is 3,890, accounting for 56.5 percent of the total of 6,883. Citations come from only 654 articles by Colorado authors, accounting for 9.5 percent across the different research fields. Within the United States, the average distance from CSU—which is located in Fort Collins, Colorado—as the geographic footprint of CSU's agriculture-related journal publications to the locations of citing papers' authors is 988.79 miles. The farthest average distance is 1,071.91 miles from CSU, in the research field of IT and data systems in food and agriculture.

Table 3—The 6,883 articles citing a randomly sampled target set of 1,202 agriculture-related journal articles by CSU authors across several agricultural research fields

Research Field	No. of citing papers in Colorado	No. of citing papers in outside of Colorado	No. of citing papers in Foreign	Average distance from CSU (miles in U.S. only)
1. Water tech & management	133 (9.8)	444 (32.7)	782 (57.5)	950.46
2. Crop inputs, Soil fertilizer, & Pest control	209 (8.3)	861 (34.4)	1,433 (57.3)	1,032.24
3. Animal health & Bio-medicine	202 (10.3)	680 (34.6)	1,086 (55.2)	976.01
4. IT and data system in food & agriculture	13 (8.9)	53 (36.3)	80 (54.8)	1,071.91
5. Bio-energy	34 (10.8)	106 (33.5)	176 (55.7)	962.49
6. Food & beverage processing & manufacturing	63 (10.7)	195 (32.9)	333 (56.3)	930.47
Total	654 (9.5)	2,339 (34.0)	3,890 (56.5)	988.79

Note: Parentheses are percent share of total citing papers

Figure 3—Heat map of the geographic footprint of papers citing CSU's agriculture-related journal publications in U.S.

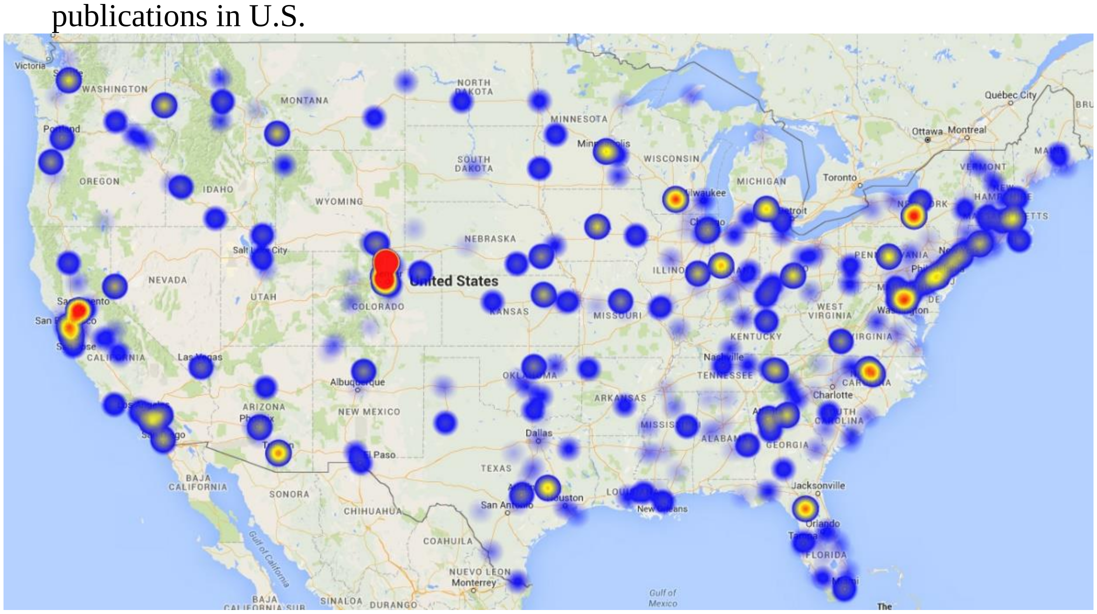
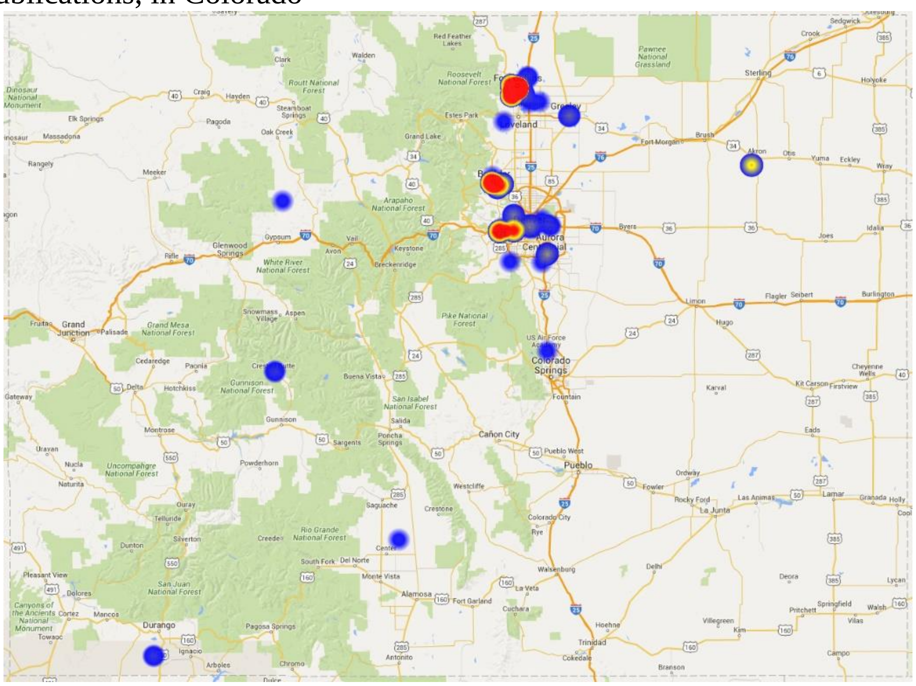


Figure 3 displays the mapping of the geographic footprint in the United States of location of authors of articles citing CSU's agriculture-related journal publications. Significantly, the relatively high densities of citing authors are located in Northern Colorado, California (especially the San Francisco area), Southern Texas, Wisconsin, Florida, North Carolina, New York, the Boston area, and so on. These geographic locations are most likely to be associated with the location of land-grant universities in the United States.

Figure 4—Heat map of the geographic footprint of papers citing CSU's agriculture-related journal publications, in Colorado



Similarly, Figure 4 displays the geographic locations of citing papers based on authors' affiliations within Colorado. Citations of CSU's agriculture-related journal publications are highly concentrated in three locations: Fort Collins (CSU), Boulder (the University of Colorado), and Golden (Colorado School of Mines and the National Renewable Energy Laboratory). Moreover, among the other minor locations are those associated with the experimental farms of the Colorado State Agricultural Experimental Station (SAES).

Therefore, knowledge spillovers of CSU's agriculture-related journal publications via the public domain mechanism have impact locally, nationally, and globally. As previous studies have pointed out, the knowledge channel of journal publications does not depend upon geographic proximity for realizing the social and economic benefits of knowledge transfers.

2. Collaboration mechanism of knowledge dissemination

The collaboration mechanism of knowledge commercialization is characterized by close interaction between university and industry, such as research collaboration or outreach activities. It is generally well suited for conveying tacit or sticky knowledge. Faculty members in the university work with colleagues in industry and the private sector in a number of ways, including consulting, conference presentations, informal consultations, collaborative research projects, co-supervising of interns, and such. However, these collaboration activities are harder to detect and to systematically measure in terms of their magnitude, size, and scope, so we proposed three proxy variables in another research paper, (Lee and Graff, 2016), such as (1) the number of industry co-authored journal publications, (2) privately sponsored grant awards, and (3) departmental level cooperative extension budgets. In this study, we utilize two of these measures that contain information about the geographic location of the collaborating industry partner--the industry co-authored journal publications and the privately sponsored grant awards--to assess the impact of the collaboration mechanism for CSU's knowledge dissemination within agriculture.

1) Grants and contracts awarded from private sector sponsors

One of the proxy variables of university traditional collaboration activities is the announced award of research funding from external sources via grants and contracts. The total value of privately sponsored grants and contracts in agriculture-related sectors from 1989 to 2012 is $17.58 million, in awards from 169 private companies. Table 4 presents summary data on grants and contracts across the different agriculturally related technologies. The average distance from CSU to the locations of private companies in U.S. is 662.90 miles and the nearest average distance is 278.87 miles, in which companies is the water technology and management.

Table 4—CSU's privately sponsored grant awards and participated companies across the different agricultural technologies

Technology	No. of firms in Colorado	No. of firms in outside of Colorado	No. of firms in foreign	Average distance from CSU (miles in U.S. only)	Amount of grants (million $)
1. Water tech & management	13 (76.5)	3 (17.6)	1 (5.9)	278.87	1.97
2. Crop inputs, Soil fertilizer, & Pest control	19 (38.8)	23 (46.9)	7 (14.3)	575.51	2.96
3. Animal health & Bio-medicine	5 (14.7)	25 (73.5)	4 (11.8)	1051.27	6.24
4. IT and data system in food & agriculture	9 (42.9)	10 (47.6)	2 (9.5)	727.26	1.28
5. Bio-energy	5 (50.0)	4 (40.0)	1 (10.0)	620.33	0.95
6. Food & beverage processing & manufacturing	16 (42.1)	19 (50.0)	3 (7.9)	570.32	4.19
Total	67 (39.6)	84 (49.7)	18 (10.7)	662.90	17.58

Note: Parentheses are percent share of total firms

The 13 companies associated with water technology located in Colorado account for 76.5 percent of all of CSU's private sector collaboration on water–related research and projects. These in-state companies have invested $1.43 million in their collaborations with CSU, which is almost 73 percent out of total private R&D investment in water-related research and projects at CSU. Moreover, there is only one foreign company, KOWACO-Korean Water Resources Corporation, and significantly, this company is strongly associated with the Department of Civil Engineering at CSU[5]. Similarly, almost 50 percent of companies associated with IT and data systems in food & agriculture, in bioenergy, and in food and beverage manufacturing technologies are located in Colorado. However, only 15 percent of the collaborating companies in animal health technology are located in Colorado.

Figure 5—Heat map of the geographic footprint, within the U.S., of private companies that have sponsored grant awards at CSU for agriculture and food related research

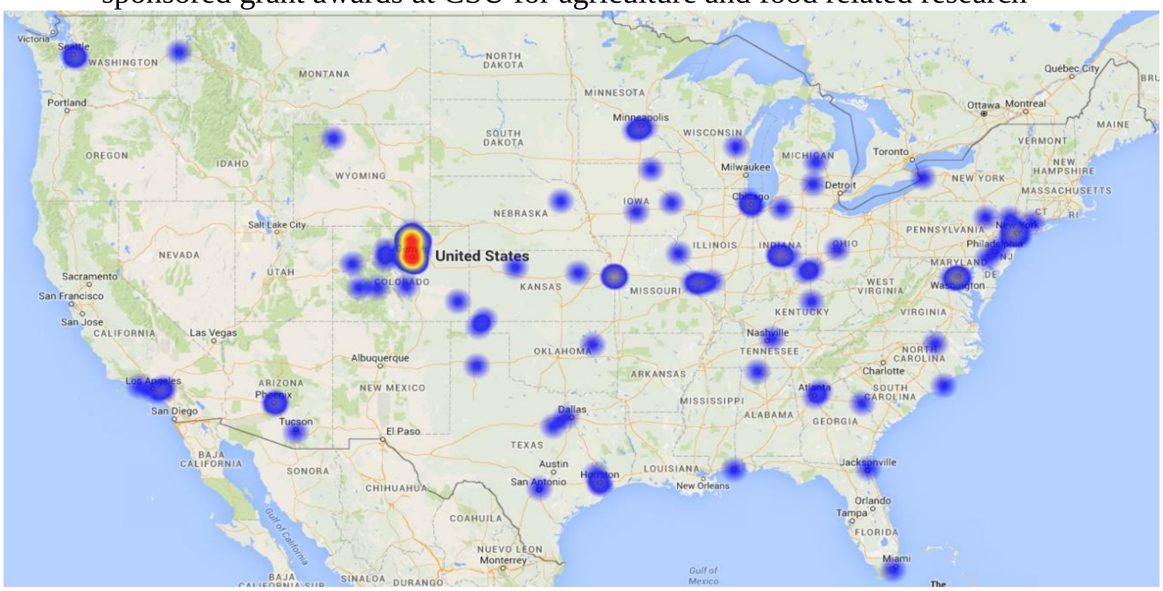
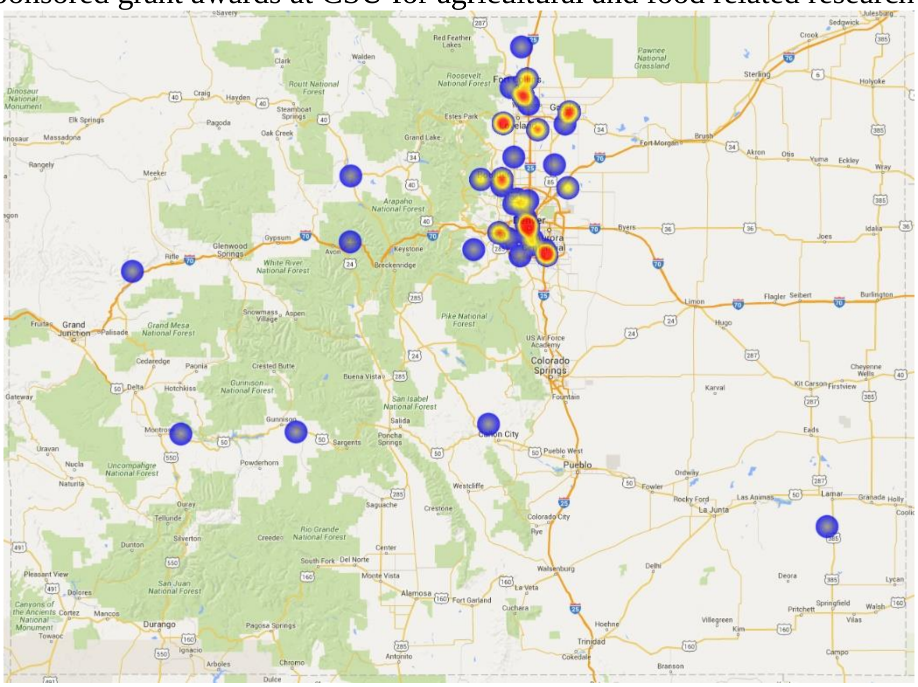


Figure 5 displays the geographic footprint across the U.S. of private firms that have awarded grants and contracts for agriculturally related research at CSU. Although sponsoring companies are distributed widely throughout the various states in the U.S., most of them are highly concentrated geographically in the northern Front Range of Colorado. Figure 6 shows the

[5] The Department of Civil Engineering at CSU and KOWACO have a sisterhood relationship, by which many faculty members in the Department of Civil Engineering at CSU have participated in national water projects in South Korea via KOWACO.

geographic footprint within Colorado, and the locations of companies are relatively compacted in the Front Range of Colorado, particularly in northern Colorado near CSU and around the Denver Technology Center (DTC) in south Denver.

Figure 6—Heat map of the geographic footprint, within Colorado, of private companies that have sponsored grant awards at CSU for agricultural and food related research



2) Industry co-authorship on academic journal articles

The industry co-authored journal publication is another indicator of the university's traditional collaboration activities. We find a total number of 290 papers written with co-authors at 194 companies. Interestingly, this particular knowledge output (the article being published) is being placed in the public domain even though the knowledge is generated through activities more closely associated with the collaboration mechanisms. As such, we assume that it may be more neutral with regards to its reliance upon the geographic proximity. However, another major characteristics of this channel is that it is significantly associated with CSU authors' social and professional research networks, as well as their capacity of collaboration activities with private sector colleagues.

Table 5—CSU's industry co-authored journal publications and co-authored companies across the different agricultural technologies or research fields

Technology	No. of firms in Colorado	No. of firms in outside of Colorado	No. of firms in foreign	Average distance from CSU (miles in U.S. only)	No. of co-authored papers
1. Water tech & management	21 (60.0)	12 (34.3)	2 (5.7)	482.85	54
2. Crop inputs, Soil fertilizer, & Pest control	9 (21.4)	25 (59.5)	8 (19.0)	854.26	55
3. Animal health & Bio-medicine	6 (16.2)	23 (62.2)	8 (21.6)	1094.93	62
4. IT and data system in food & agriculture	12 (48.0)	13 (52.0)	0 (0.0)	636.48	31
5. Bio-energy	6 (42.9)	7 (50.0)	1 (7.1)	758.92	19
6. Food & beverage processing & manufacturing	10 (24.4)	24 (58.5)	7 (17.1)	622.07	69
Total	64 (33.0)	104 (53.6)	26 (13.4)	749.92	290

Note: Parentheses are percent share of total firms

By comparison with Table 4 in the previous section, in Table 5 the average distance is 749.92 miles, which is a little bit longer than the privately sponsored grants and contracts measure of the collaboration channel, 662.90 miles, but the other evidence is quite similar to the privately sponsored grants and contracts. By the same token, Figure 7 displays the geographic footprint of co-authors from private companies and it is virtually identical with that of Figure 5, with a relatively high density of private sector co-authoring companies located in Colorado. However, there is some contrast between Figure 6 and 8, with the locations of co-authors from private companies more highly concentrated near CSU. This may be related with the locations of startup companies affiliated in CSU, whose employees might be faculty members, research staffs, or graduate students in CSU and thus actively co-authoring with others at the university.

Figure 7—Heat map of the geographic footprint of companies in the U.S. that have co-authored journal publications with CSU researchers in agriculturally related fields

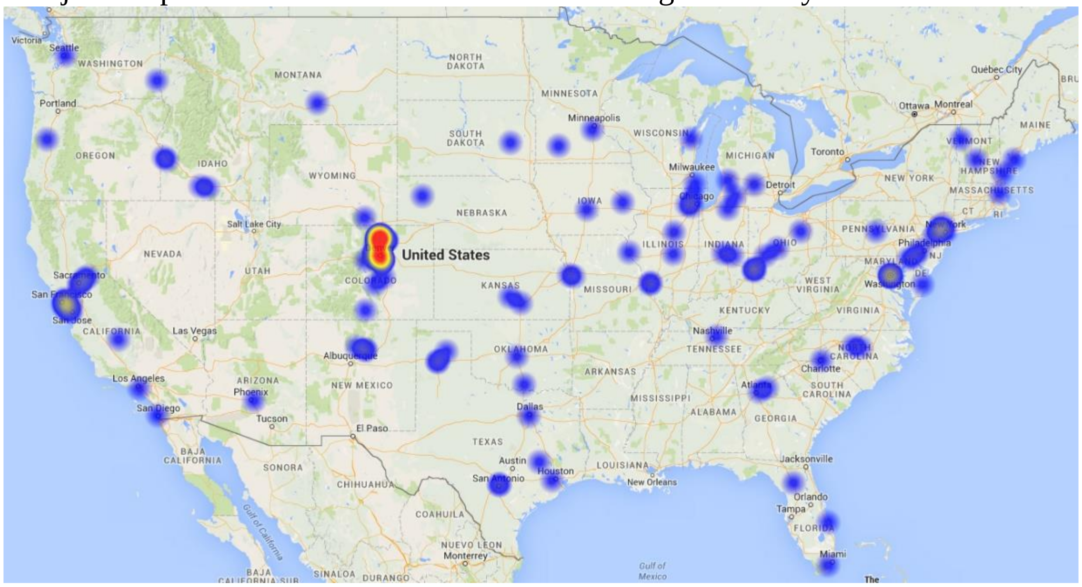
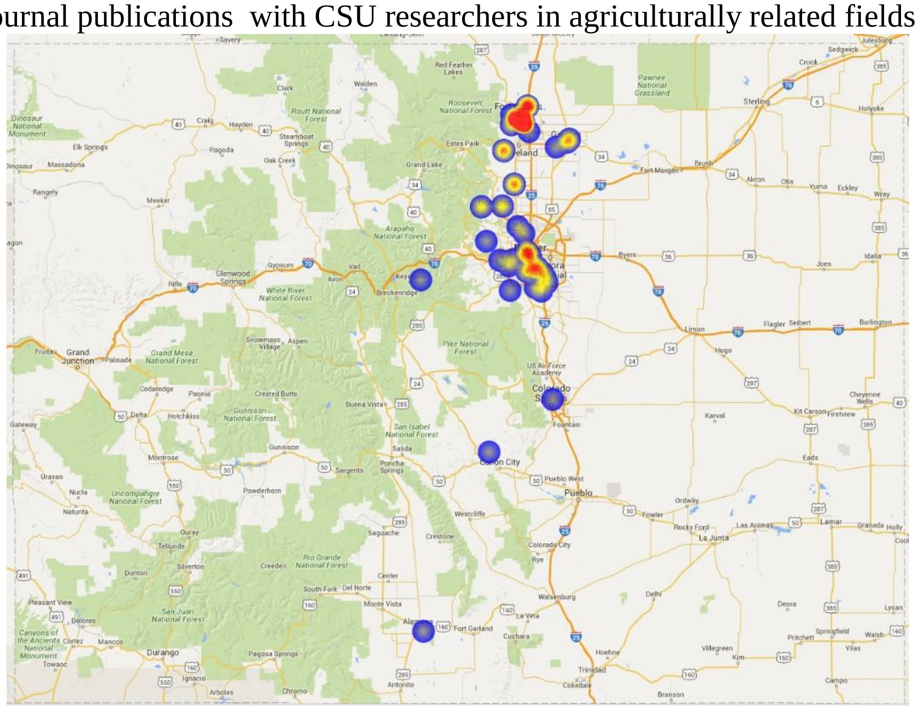


Figure 8—Heat map of the geographic footprint of companies in Colorado that have co-authored journal publications with CSU researchers in agriculturally related fields



Privately sponsored grants and contracts and industry co-authored journal publications as proxy measures of the traditional collaboration mechanism of knowledge dissemination are most likely to involve sticky or tacit forms of knowledge and information, because the mechanism has relatively higher transaction costs and capacity requirements. It is possible to exclude others from accessing (at least some key aspects of) this knowledge, by virtue of its intrinsic stickiness, merely by not including them in the collaborative relationship.

Therefore, geographic proximity is relatively more important than that observed for the public domain mechanism of disseminating knowledge through journal publications. Within these two measures of traditional collaboration, we find the geographic location of industry co-authors on journal articles have a longer average distance from CSU, perhaps because it involves more codified forms of knowledge than the other measure of grant and contract awards from private sponsors.

3. Patenting/licensing mechanism of knowledge dissemination

The patenting and licensing mechanism for knowledge commercialization, which is characterized by the utilization of the intellectual property rights (IPRs) and licensing contracts to control access, is best suited when a certain degree of excludability is required to create sufficient incentives for follow-on investments in otherwise non-excludable and non-rivalrous knowledge outputs.

To better understand the impact of CSU's patents as one of the newer mechanisms of university knowledge dissemination, we utilize citation mapping. In general, citation mapping of patents consists of connecting cited and citing references (backward and forward, respectively), which allows us to track the relationships between existing and new technologies, as well as the impacts of the existing technologies on the emergence of new technologies in the field. CSU inventors had filed for protection on 76 inventions in agricultural and food related technologies. Our analysis found 1,868 newer patents had made citations to these already existing CSU patents and patent applications. Table 6 summarizes data on these citing patent documents across the different technologies in agriculture.

Table 6—Patent documents citing CSU's portfolio of patent applications and granted patents across the different agricultural technologies

Technology	No. of citing patents in Colorado	No. of citing patents in outside of Colorado	No. of citing patents in foreign	Average distance from CSU (miles in U.S. only)
1. Water tech & management	0 (0.0)	25 (71.4)	10 (28.6)	1278.18
2. Crop inputs, Soil fertilizer, & Pest control	11 (8.0)	103 (75.2)	23 (16.8)	1037.57
3. Animal health & Bio-medicine	187 (29.3)	329 (51.5)	123 (19.2)	888.06
4. IT and data system in food & agriculture	25 (4.7)	466 (87.3)	43 (8.1)	994.82
5. Bio-energy	6 (2.0)	233 (77.9)	60 (20.1)	1303.70
6. Food & beverage processing & manufacturing	16 (7.1)	145 (64.7)	63 (28.1)	886.25
Total	245 (13.1)	1301 (69.6)	322 (17.2)	1001.87

Note: Parentheses are percent share of total citing patents

As shown as Table 6, the average distance from CSU to the locations of citing patents' inventors is 1002 miles, which is similar to the average distance seen for the public domain knowledge dissemination channel (as measured by distance to authors of journal publications citing CSU research) and longer than the collaboration knowledge dissemination channel (as measured by privately sponsored grants and industry co-authors on journal publications). Thus, by virtue of the slippery nature of information codified within patents, geographic proximity is unimportant for realizing benefits of any associated spillovers, at least other inventors learning about the new technology disclosed by the patent documents. Still, it is possible to exclude others from accessing and using the technology described in the patents. It should also be pointed out that access can be limited in other countries as well by taking out patents and licensing them. We note that the percent share of foreign inventors citing CSU's patents is relatively much smaller than the percent share of foreign authors citing CSU's journal publications, accounting for 17.2 and 56.5 percent, respectively.

Figure 9—Heat map of the geographic footprint in the U.S. of inventors on patents that cite CSU's agriculturally related patent applications and granted patents

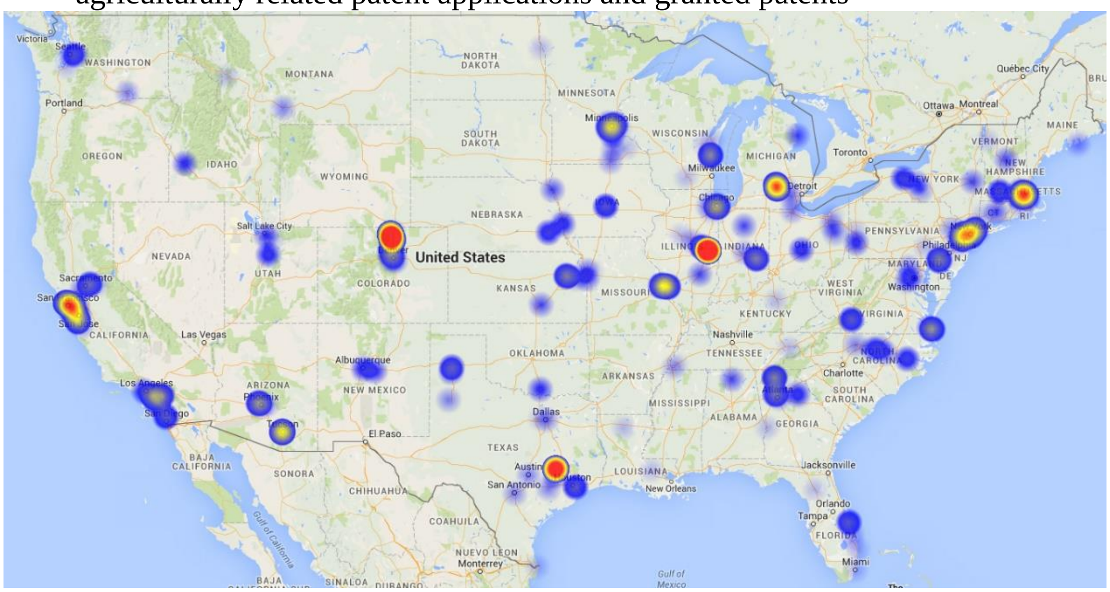
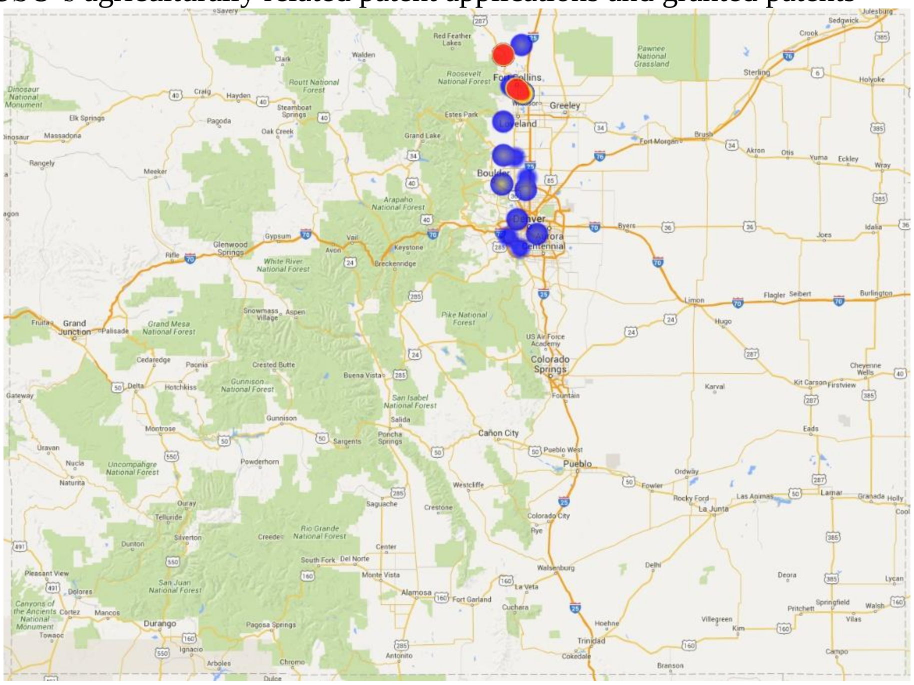


Figure 9 displays the geographic locations of the inventors on patents that are citing CSU's agricultural technology patents. This map demonstrates the commercial spillovers of the CSU's agriculture-related research throughout the U.S. The distribution of the geographic footprint is similar to that of authors citing CSU's agricultural journal publications in Figure 3, but not all of the geographic locations are the same. It seems reasonable to assume that the distinction between citing patents and citing papers can be explained by not only by the different magnitudes of citation rates, but also the different characteristics of knowledge dissemination channels. Both channels specialize in relatively slippery forms of knowledge, but the patents have an invoked exclusion by virtue of IPRs.

Figure 10—Heat map of the geographic footprint within Colorado of inventors on patents that cite CSU's agriculturally related patent applications and granted patents



Similarly, Figure 10 shows the location of inventors within Colorado that are citing CSU's agricultural patents. Of these, 91 percent are concentrated near CSU and elsewhere in the northern Front Range, and we observe that many of these areas are strongly associated with the CSU's startup companies. Therefore, spillovers via the patenting/licensing mechanism for knowledge dissemination, appears to have a wide impact on commercial innovation in agriculturally-related sectors. While a patented invention is a codified or slippery form of knowledge, it is possible to exclude others from accessing and making use of it, which is the key distinction from research results only disseminated via journal publications through the public domain mechanism.

4. Venture creation mechanism of knowledge dissemination

The venture creation mechanism of knowledge commercialization is perhaps best suited for raising private investment in the further development of knowledge, treating that knowledge most like a private good, which has intrinsic stickiness or context dependence, making it possible to exclude others from accessing this knowledge. Both patenting/licensing and venture creation are newer mechanisms of knowledge disseminations, distinguished from some of the more traditional industry collaboration activities. Table 7 summarizes data about the CSU's startup companies across several different technologies in agriculture. Almost 90 percent of startup companies are located in Colorado, mostly near the CSU campus, and one company recently has been moved from Fort Collins, CO, to Navasota, TX.

Table 7—CSU's startup companies across the different agricultural technologies

Technology	Startups in Colorado	Startups in outside of Colorado	Startups in foreign	Average distance from CSU (miles in U.S. only)
1. Water tech & management	1 (100.0)	0 (0.0)	0 (0.0)	5.00
2. Crop inputs, Soil fertilizer, & Pest control	2 (100.0)	0 (0.0)	0 (0.0)	27.00
3. Animal health & Bio-medicine	3 (75.0)	1 (25.0)	0 (0.0)	257.75
4. Bio-energy	2 (100.0)	0 (0.0)	0 (0.0)	12.50
5. Food & beverage processing & manufacturing	2 (100.0)	0 (0.0)	0 (0.0)	33.50
Total	10 (90.9)	1 (9.1)	0 (0.0)	107.45

Note: Parentheses are percent share of total startup companies

As shown as Figure 11, the geographic locations of the startup companies are almost entirely limited to Colorado, and in Figure 12, about 90 percent of the startups are located near CSU in the northern Front Range. Thus, the venture creation mechanism is highly reliant upon geographic proximity, involving quite sticky knowledge and context dependence, it has much higher transaction costs and capacity requirements than the other knowledge dissemination channels we have considered.

Figure 11—Heat map of the geographic footprint in the U.S. of CSU's agricultural and food related startup companies.

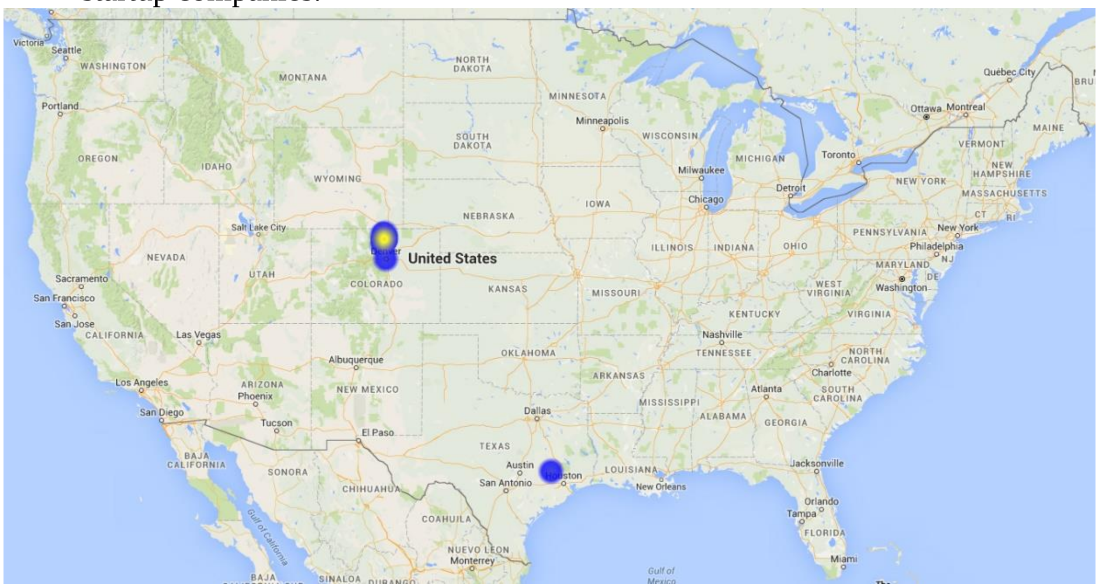
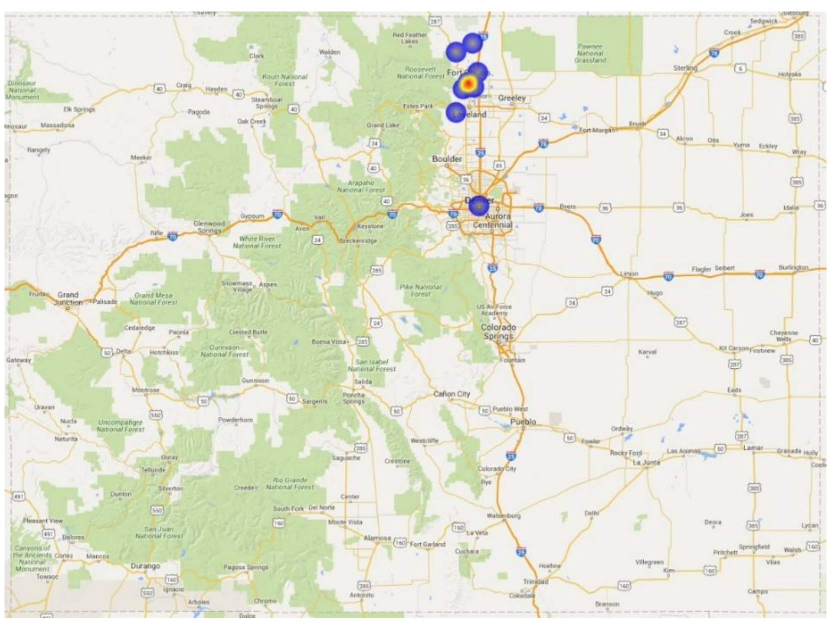


Figure 12—Heat map of the geographic footprint within Colorado of CSU's agricultural and food related startup companies.



B. Non-parametric tests of university knowledge dissemination channels

In this section, we attempt to examine the different degrees of knowledge "stickiness" across CSU's dissemination channels by estimating the one-sample Kolmogorov-Smirnov non-parametric test, which is based on Kolmogorov (1933), Smirnov (1933), and Conover (1999). This test involves measuring a random sample from some unknown distribution for testing the null hypothesis, which specifies some distribution function, $F^*(x)$ as cumulative distribution functions.

A random sample $X_1, X_2, \cdots, X_n$ is drawn from some population, such as geographic distances of university knowledge spillovers, and it is compared with the true distribution function of the random sample, $F^*(x)$. In the test, we hypothesize that the true distribution is a normal distribution. In order to compare the random sample with $F^*(x)$, the empirical distribution function of the random sample is defined by Definition (1)[6]

Definition (1) Let $X_1, X_2, \cdots, X_n$ be a random sample. The empirical distribution function, $S(x)$, is a function of *x*, which equals to the fraction of $X_i s$ that are less than or equal to *x* for each *x*, $-\infty < x < \infty$.

The equation (1) represents the empirical distribution function and where, $I_{[-\infty,x]}\left(X_i\right)$ is the indicator function, which equals to 1 if $X_i \le x$ and equals to zero if otherwise.

$$S(x) = \frac{1}{n}\sum_{i=1}^{n} I_{[-\infty,x]}\left(X_i\right) \tag{1}$$

[6] W.J, Conover (1999)

So, this test definition can compare the empirical distribution function, $S(x)$, with the theoretical distribution function, $F^*(x)$, to see if there is good agreement.

The geographic distances of university knowledge spillovers data consist of a random sample, $X_1, X_2, \cdots, X_n$, of size *n* associated with some unknown distribution function, denoted by $F(x)$.

Hypothesis (1)[7] Let $F^*(x)$ be a completely specified theoretical distribution function as a normal distribution: Two-sided test

$$\begin{cases} H_0 : F^*(x) = F(x) \ \forall x \ \textit{from} -\infty \textit{ to } \infty \\ H_1 : F^*(x) \neq F(x) \ \textit{for at least one value of } x \end{cases}$$

Suppose that the Kolmogorov-Smirnov statistic, *D*, be the greatest vertical distance between the empirical distribution function, $S(x)$, and the theoretical distribution function $F^*(x)$, which is the equation (2) below.

$$D = \sup_x \left| F^*(x) - S(x) \right| \tag{2}$$

Where the "*D*" equals the supremum, over all *x*, of the absolute value of the difference, $F^*(x) - S(x)$.

Thus, for testing the "stickiness" or the characteristic behaviors of the tacit versus codified forms of university knowledge, the one-sample Kolmogorov-Smirnov non-parametric tests (K-S tests) and its CDFs can be used to compare empirical distribution function and the normal distribution function across the different types of university knowledge dissemination channels.

[7] W.J, Conover (1999)

Table 8 shows summary statistics of the geographic distances from the location of CSU to the indicated recipients of spillovers, across the different knowledge dissemination channels. (The table considers only distances to those in the United States; it excludes foreign distances.) As shown in previous sections, the mean distance between CSU and the location of authors on citing papers and the location of inventors of citing patents in the United States, is the farthest geographic distance, similar to each other. Thus, these channels seem to involve more slippery forms of knowledge the spillovers of which are less likely to be geographically bounded. Figure 13 displays the results of the K-S nonparametric tests, which consist of D-values and their statistical probability values, and the CDFs of the geographic distances from the location of CSU across the different knowledge dissemination channels in the United States.

Table 8—Summary statistics: Geographic distances from the location of CSU (U.S. only) across the different knowledge dissemination channels

	Summary Statistics (U.S. miles)				
Knowledge Channels	**Obs.**	**Mean**	**Std. Dev**	**Min**	**Max**
Citing papers	2,989	988.79	637.99	5	3,037
Privately sponsored grant awards	148	662.90	623.33	5	1,852
Industry co-authored papers	167	749.92	676.79	5	3,010
Citing patents	1,546	1,010.27	550.24	5	2,183
Startups	11	107.45	298.67	5	1,006

The one-sample nonparametric test results show that the K-S tests reject the null hypothesis at a 1% level of statistical significance, which means the empirical distributions cannot converge to a normal distribution. In other words, at the given level of significance, $\alpha = 0.01$, the K-S statistical value exceeds the critical value of the quantiles of the K-S test statistic. However, it is still meaningful for testing the sticky versus slippery mechanisms of university knowledge dissemination channels by assessing the CDFs and K-S's D-value.

Figure 13—The CDF plots and one-sample Kolmogorov-Smirnov non-parametric tests: Geographic distances from the location of CSU (U.S. only) across the different knowledge dissemination channels

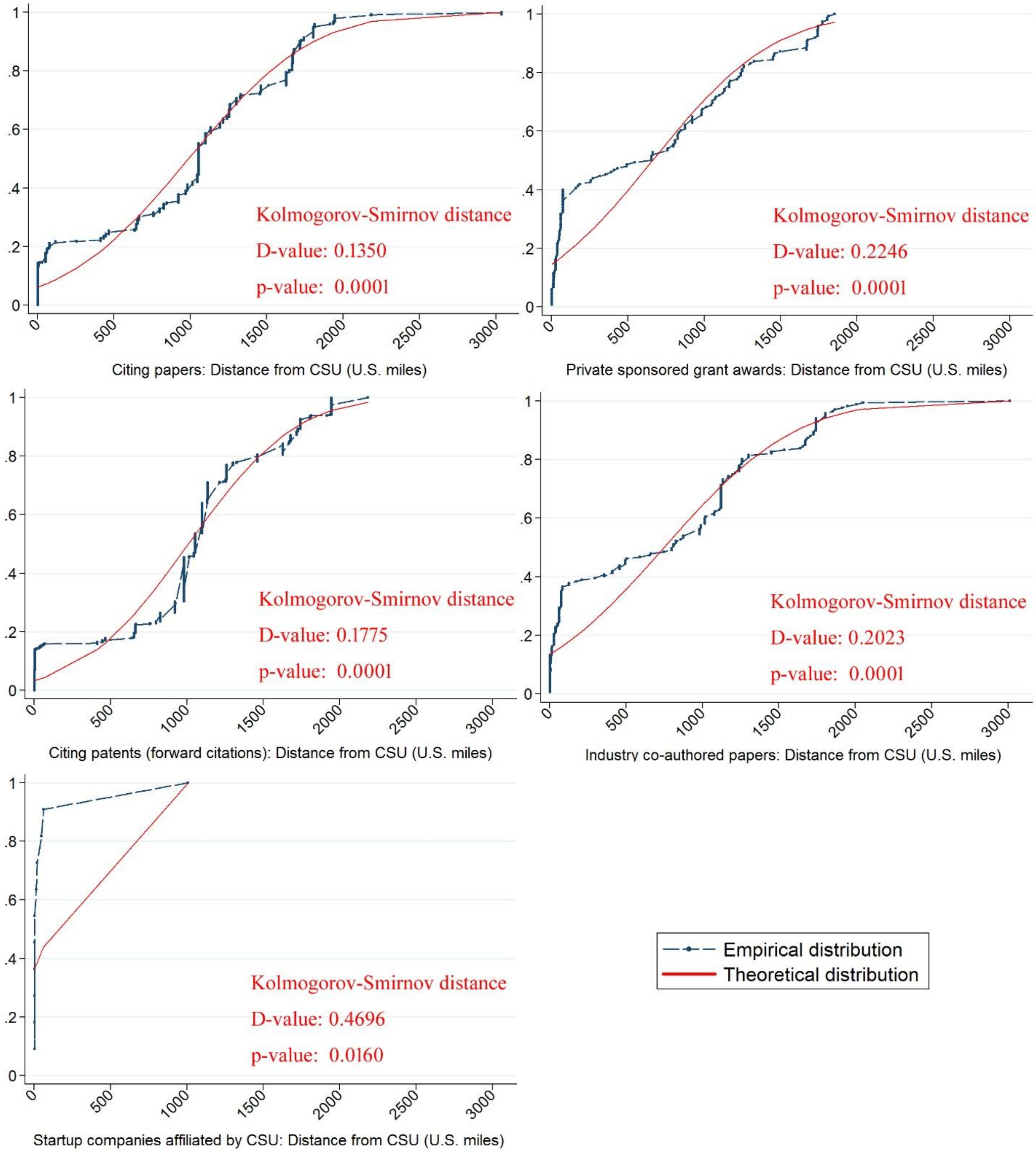


Figure 13, the citing papers, has the smallest D-value of all, which means the distribution of citing papers is more likely to converge to a normal distribution than the others, even though it is insignificant. Thus, the channel cannot be localized but, rather, involves a slippery form of knowledge. The CDF plot seems not to be highly skewed within 300 miles but rather to be extended over several thousand miles. Similarly, the CDF plot of citing patents is less likely to be within the local Colorado, but it is highly skewed around 1,000 miles, with the maximum distance between CSU and the citing patents being 2,183 miles, which is shorter than citing papers.

It is highly probable that the inherent characteristics of both knowledge dissemination channels pursue non-rivalrous, but the patents involve a certain degree of excludability by utilizing intellectual property rights and contracts, so the citing patents are likely to involve a less slippery form of knowledge than citing papers.

Of particular interest is the collaboration mechanism of knowledge dissemination channels. The privately sponsored grant awards and industry coauthored papers are localized to within 200 or 300 miles, accounting for almost 40 percent, so these channels involve a much more sticky form of knowledge, and geographic proximity is significantly more important for these collaboration activities. Nevertheless, they have different scopes of geographic locations. In Table 8, the maximum distance between CSU and industry coauthored articles is much longer than the maximum distance for privately sponsored grant awards—3,010 miles and 1,852 miles, respectively—because again of the heterogeneous features between the channels. It should be pointed out that the inherent characteristics of industry coauthored journal articles pursue not only the public domains but also collaboration mechanisms of knowledge dissemination, so it is less likely to have a sticky form of knowledge than the privately sponsored grant awards. In addition, the D-value of industry coauthored journal articles is smaller than that of the privately sponsored grant awards.

Finally, the start-up companies affiliated with CSU appear to involve the stickiest form of knowledge, and their D-value is much larger than other channels at 0.4696. Thus, the start-up companies are highly localized, within 10 or 20 miles of the university, for almost 90 percent of the start-ups, because most of the founders and employees are CSU faculty members, research staff, or GRAs, as well as local, private entities. In addition, the early stage of start-up companies needs support from their original university (e.g., for the utilization of university facilities and equipment), which is the most important knowledge and technological pipeline of start-ups.

V. Conclusions

Despite debate about the geographic proximity of university-industry collaborations, university knowledge spillovers does appear to generate localized impacts on regional commercial innovation that are likely to beneficial both to private industry and the public. Particularly in agriculture, the land-grant universities play a significant role in agricultural research and innovation in the agribusiness sectors. However, rather than thinking that “one size fits all,” the spillover benefits from university knowledge generation should be considered by the different types of dissemination channels that are utilized. In this study, we have focused on Colorado State University (CSU)’s knowledge spillovers within agriculturally related fields and technologies.

We have examined the various mechanisms of university knowledge spillovers and the geographic scope of impact on the agricultural economy associated with each. We find evidence that academic knowledge spillovers are geographically bounded, but they are not strictly limited to the regional scale. Crucially, the impact of university spillovers on agriculturally-related industries depends upon which type of knowledge dissemination channel or transfer mechanism is utilized by university researchers. Broadly speaking we evaluate four types of channels—including the public domain or publication mechanism, the industry collaboration and extension mechanism, the technology patenting/licensing mechanism, and the venture creation mechanism—each of which are variously adapted to transmitting different degrees of sticky (tacit) versus slippery (codified) knowledge.

Our findings show that the spillover impacts of journal publications, through the public domain mechanism of knowledge dissemination, are rarely localized within Colorado; rather, the geographic scope of these impacts is national and even global. Thus, geographic proximity is not a question with this channel. However, the extent to which the spillover impacts of patented knowledge is localized within Colorado is open to question because it is possible to control permissions for use, but at the same time it is impossible to limit everyone's awareness and use of it, particularly in foreign jurisdictions where patents are not taken out by the university. Therefore, the degree of localization of university knowledge spillovers when using the patent and licensing mechanism might depend on the different types of technology involved as well as the intellectual property and contract strategy pursued. Thus, university journal publications and patents are most appropriate for dissemination of more slippery forms of knowledge, but commercial innovation impacts can be localized nearer to the location of a university when using patents and licensing than when using journal publications alone.

However, the collaboration mechanism of knowledge dissemination, such as indicated by industry coauthorship on journal articles and private sponsorship of grants and contracts, which are more rivalrous by virtue of the more tacit qualities of knowledge being disseminated and because of the higher transaction costs, requires closer interaction and greater geographic proximity, which usually prevents global dissemination . Thus, we observe geographic proximity is significantly important for these channels. However, there are even distinctions within these. For example, we find industry coauthorship on articles to be less likely to be localized than privately sponsored grant awards. Finally, university start-ups are highly geographically bounded near universities because in the early stages start-up companies need support from their host university.

One conclusion we can draw from this study is that both public and private benefits of university knowledge transfers rely on the different types of knowledge dissemination channels and the intrinsic characteristics of the different types of knowledge being disseminated. Moreover, our unique data set of Colorado State University's research activities and a full range of potential knowledge dissemination channels make it possible to examine the extent to which the different types of knowledge dissemination channels work within the context of agricultural fields and technologies. Most previous studies of university-industry collaboration activities have used aggregate data.

Despite these interesting preliminary findings, there are at least two major shortcomings in our approach. First, which we hope to address in further studies, we will attempt to build relevant regression models for measuring university knowledge spillovers, via mechanisms of knowledge dissemination for both sticky and slippery types of knowledge. Second, although both advantages and disadvantages exist for the use of single institutional data, it may compromise findings' generality relative to other institutions or to more aggregate economy-wide data because each institution has its own idiosyncratic conditioning characteristics, including levels of research expenditures, management skills, administrative policies, and so on. Thus, we hope to add more institutional data and compare the results.

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