Funds for some, spills for others:

The spatial dimensions of nanotechnology development in China

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Abstract

By acquiring the capabilities to take a global lead in the development of an emerging technology system, less developed countries can rapidly hasten the process of their technological catching up or forging ahead. In this context, nanotechnology represents a set of science-based enabling technologies that are still in the early stages of their technological life cycles and that promise significant long-term pay offs to countries pioneering their development and commercialization. This paper investigates the factors driving nanotechnology development in Chinese regions. Although advanced regions of China have spearheaded the country's rapid growth in nanotechnology, other regions are increasingly involved in the development of this technology. Results from a dynamic panel data analysis suggest that different institutional and policy factors have been driving nanotechnology development in regions with different scientific capabilities. While governmental financing exerted a major impact on the growth of nanotechnology in regions with superior scientific capabilities, in regions lagging in this, it was knowledge spillovers from other regions through the collaboration network of scientists that proved vital. The results point to the need for a reconfiguration of policies that govern nanotechnology funding in China such that mechanisms are in place to ensure inter-regional collaborations that can augment technological convergence among Chinese regions.

Keywords: Nanotechnology; Geographic proximity; Institutions; Collaboration; Knowledge spillovers; Chinese regions; Publications and patents.

JEL Codes: O31, O33, R12

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1. Introduction and background

For less developed countries, who typically occupy follower positions in mature technologies that have long lost their dynamism, a 'real' catching-up process requires acquiring the capability to develop a new technology system (Perez and Soete 1988). Such a system provides enormous opportunities for successive improvements across a range of technologies, generating economy-wide technological externalities that can last several decades. An early entry into a new technology system therefore can trigger faster catching up and long run success.

In this respect, nanotechnology represents a set of science-based enabling technologies that are still in the early stages of their technological life cycles and that promise significant long-term pay offs to countries engaging in their development and commercialization. Studies have shown that nanotechnology can serve as a general purpose technology that has applications across a broad spectrum of economic activities spanning almost all fields of manufacturing (Shapira and Youtie, 2008; Wang et. al. 2013). In other words, countries that occupy frontier positions in nanotechnology are likely to lead in many fields of innovation in the years to come.

Large less developed countries with a strong scientific-research tradition, such as China, have long been expected to provide global leadership in emerging science-based technologies such as biotechnology and nanotechnology (Niosi and Reid, 2007). In this respect, over the last decade or so, as China began undergoing its transformation from an investment-driven to an innovation-driven economy, the country experienced dramatic progress in the development of nanotechnology. The scientific output in nanotechnology from China, as measured by nanotechnology-related publications with a Chinese address, has been increasing exponentially. Whereas in 2000 the number of nanotechnology-related publications from China stood at a paltry 30% of the US level, by 2013 it rose to 140%[1]. The same period also witnessed a remarkable increase in the number of annual nanotechnology-related patent applications filed locally, from 275 in 2000 to 6,333 in 2010.

Financial support from the state is generally viewed as a vital ingredient to the emergence of a new technology system. Private sector investment in such a system, especially in the early stages, will be less than optimum because of the high levels of uncertainty about the technological outcomes but also the commercial potentials of the newly-developed

[1] These figures are based on the data collected from Web of Science.

technologies. In China, nanoscience and nanotechnology drew favourable policy interest already in the 1980s when these concepts first emerged. However, serious efforts to promote nanotechnology began only in 1990 when the Ministry of Science and Technology launched the ten-year “Climbing-Up” project (Bai 2001, Tang, Wang & Shapira 2010). Soon after, the concept began trickling through the scientific ranks and the Chinese Academy of Sciences (CAS), the National Natural Science Foundation of China (NSFC), and the State Science and Technology Commission (SSTC) began funding nanoscience-related activities (Chunli Bai, 2005). Today, according to the China Association for Science and Technology, the three most widely used high-tech words in China are “computer”, “gene”, and “nanometer”.

In this paper, we examine the growth of nanotechnology in China with a particular focus on whether the drivers of this growth vary across Chinese regions with different scientific capabilities. We argue that the large-scale governmental aid for nanotechnology development would have made a notable impact only in regions possessing high scientific capabilities. Regions lagging behind in scientific capabilities would not have the necessary complementary resources either to be major beneficiaries of government support in the first place or to make an efficient use of the support received from the state. However, we suggest, drawing on the economic geography literature, that lagging Chinese regions can leverage their scientists’ formal collaboration links to bring in spillovers of nanotechnology from other regions. The collaboration network of scientists acts as an important institutional resource for lagging regions, partly compensating for their weak scientific capabilities. Our focus on the differential sources of nanotechnology development contributes to the economic geography literature on knowledge spillovers and to the catch up literature that stresses the development of a new technology system for faster catching up. Given especially that governmental funding in the near future is likely to remain biased against lagging regions where scientific capabilities are still low, this study offers important policy lessons for ensuring a more balanced technology development across Chinese regions than is currently the case.

The following section provides a theoretical and empirical background to the study and raises the specific questions for empirical scrutiny. The third section presents the data and explains the methods. The results of the empirical analysis are discussed in the fourth section, while the final section draws policy implications and concludes.

2. Background and research questions

2.1 Nanotechnology as a technology system in the context of China

Both the traditional catch up literature (e.g. Gerschenkron, 1962) and the new-growth theories (Grossman and Helpman 1991; Rivera-Batiz and Romer 1991) stress the role of international technology diffusion for the catching up of less developed countries to the income levels of developed countries. In both these perspectives, mature technologies developed in advanced countries represent a major opportunity that less developed countries might exploit so they can avoid the costly, time consuming, and challenging task of developing new technologies from scratch. However, another perspective, whose spirit we embrace in this paper, emphasizes the importance of less developed countries taking a leadership role in the development of a new technology system (Perez and Soete 1988). Such a system, in this view, impacts growth in a broad range of sectors and generates economy-wide knowledge spillovers, thereby accelerating a country's catching-up process.[2] In this context, given that nanotechnology has applications in a wide spectrum of activities, a leadership position in nanotechnology implies a significant 'window of opportunity' for a large less developed country like China to accelerate its catch up to the global techno-economic frontier.

In developing a science-based technology like nanotechnology, less developed countries are not particularly at a comparative disadvantage vis-à-vis developed countries. This is because many in the former category of countries, and in particular China, possess world-class universities and research institutes that boast of a rich heritage in scientific research. Furthermore, realizing the tremendous potential of nanotechnology, China has been adopting an ambitious nanotechnology development strategy. Key to this has been extensive financing of nanotechnology research under the National Natural Science Foundation program. China's efforts to promote nanotechnology are aimed at setting off a second technological wave in the country, following the substantial progress made by China in information and communication technologies over the past decade (Lazonick and Li, 2012; Lazonick, 2004; Lu, 2000).

[2] Well-known examples of this process are South Korea and Taiwan which focused early on in developing the electronics industry, at a time when this industry was fast emerging and when both countries had little prior experience in this or related industries.

2.2 The geography of knowledge development

That technological development tends to be unevenly distributed across regions (or countries), with high-technology activities in particular spatially concentrated, is well understood in the literature (Henderson, 2003; Niosi, 2001; Antonelli, 2001; Niosi and Queenton, 2010). In China, given the wide regional inequality in scientific capabilities, the emergence of nanotechnology unavoidably started in a small number of leading regions. However, few studies have explored the geographic dimensions of nanotechnology development in China. Motoyama, et al. (2014) was one of the first attempts to address the question of regional convergence or divergence of nanotechnology development in China. Adopting a spatial correlation technique, they found very little diffusion of knowledge from leading regions to lagging regions and predicted that the tendency towards regional divergence would persist. We, however, suggest that for a fuller understanding of regional dimensions of knowledge development in a large country like China, it is important to go beyond the traditional spatial proximity framework and take into account inter-regional knowledge flows that may occur through scientists' formal collaboration networks. This is because, as we discuss below conceptually and in section 4 empirically, diffusion of knowledge via collaboration networks can compensate for the initially weak innovation systems of lagging regions.

2.3 Channels of knowledge flows

A vast body of research has examined the spillovers of knowledge across regions, nations, firms or industries (for reviews see, Frenken et al. 2010; Wang et al. 2013; Jacob & Meister, 2005). A dominant strand of this literature emphasizes that knowledge externalities occur locally, rather than globally (Jaffe 1989; Antonelli 2001; Verspagen and Schoenmakers, 2004; Arundel and Guena, 2004; Abramovsky and Simpson, 2008). The localized character of knowledge spillovers, the argument goes, stems from the tacit nature of knowledge. This renders the acquisition of knowledge simply from technology blueprints difficult, and therefore calls for close, often informal, people-to-people interactions. Zucker, et al (1998) is explicit about the specific mechanism of knowledge flows, pointing to the role of the social network of former students, teachers, and colleagues as a knowledge diffusion mechanism within a specific location.

There is growing evidence, however, that geographic distance is not a limiting factor for knowledge spillovers. Formal linkages, such as co-authorship ties, can facilitate knowledge flows over long distances (Cockburn and Henderson, 1997; Ponds et al, 2009). These linkages provide an important means for regions or countries to tap into the resources and knowledge of more advanced regions or countries. Several studies have documented the fast growth of collaboration in science, with some highlighting that international collaborations generate higher quality research (higher citation rates) than domestic collaborations (Frenken et al. 2010; Tang and Shapira, 2011) or facilitate entry into new research fields (Tang and Shapira, 2011).

2.4 Empirical framework and Research questions

Drawing on the preceding discussion, we propose an empirical framework for understanding the development of nanotechnology in Chinese regions. Two factors are integral to explaining the growth in nanotechnology across Chinese regions in our framework: (1) the sizeable governmental financial support, and (2) inter-regional and international knowledge spillovers. We treat collaboration networks as the main conduits of knowledge spillovers, but we also account for potential spillovers stemming from the geographic proximity between regions. Given that collaboration networks evolve over time, we treat collaboration as a dynamic construct; existing literature has paid only scant attention to the dynamic aspect of collaboration due primarily to the use of cross sectional data.

A particular novelty of our study is that we carryout separate analysis for leading and lagging regions in scientific capabilities. The dynamics of knowledge development in these two sets of regions are likely to be different. Even if advanced and lagging regions received the same level of funding, they would likely generate differential returns just because the former regions can leverage their superior capabilities to generate greater *bang for the buck* compared to the latter regions wherein funds would be less efficiently utilized. Nevertheless, lagging regions can benefit from collaborations between their scientists and those from advanced regions. The benefits for advanced regions through these collaborations are likely minimal (aside from the goodwill they have gained).

Drawing on the discussion so far, we propose the following research questions for empirical examination.

- To what extent has funding for nanotechnology research by the Chinese government succeeded in stimulating the development of nanotechnology in Chinese regions?
- To what extent have collaboration networks and geographic proximity generated inter-regional spillovers of nanotechnology knowledge?
- Do differences in the scientific and technological capabilities of regions affect the extent to which regions benefit from state funding and from knowledge spillovers? Specifically, do lagging regions benefit more from regional spillovers

than from state funding, and vice versa?

3. Data and variables

For the econometric analysis, we use a panel data set of 30 Chinese regions[3] spanning 11 years (2000-2010). The dependent variable captures a region's nanotechnology output, measured by patent applications filed by inventors from a Chinese region at China's State Intellectual Property Office (SIPO). We employ over 30,000 nano patent applications gathered from the China Patents Full-text Database[4].

The key independent variables are 'nano funding' that a region received for nanotechnology research from the National Natural Science Foundation; inter-regional spillovers; and international spillovers. Inter-regional spillovers in our framework stem from two sources: one is the nanotechnology-related patents of a region, and the other is the nano funding received by a region. We identify two carriers of spillovers: the collaboration network of scientists and the geographic proximity between regions. The first of these carriers is defined in terms of a dynamic collaboration matrix as follows:

$$\begin{bmatrix} P_{1,1,t} & P_{1,2,t} & \cdots & \cdots & \cdots & P_{1,30,t} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \vdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \vdots \\ P_{i,1,t} & \cdots & \cdots & P_{i,j,t} & \cdots & \vdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{30,1,t} & \cdots & \cdots & \cdots & \cdots & P_{30,30,t} \end{bmatrix}$$

In the matrix, an element P_{ijt} is the number of co-authored nano publications involving regions i and j in year t. The spillovers from patented technologies ($\text{TECHSPILL}_{\text{it}}$) and nano funding ($\text{FUNDSPILL}_{\text{it}}$) that region i receives from all other regions are defined respectively as:

$$TECHSPILL_{it}^{collab} = \frac{\text{PUB}_{ijt}}{\text{PUB}_{\text{jt}}} * PAT_{jt} \text{ (i, j=region1, region 2, ..., region 30, i} \neq \text{j)} \quad (1)$$

$$FUNDSPILL_{it}^{collab} = \frac{\text{PUB}_{ijt}}{\text{PUB}_{\text{jt}}} * F_{jt} \text{ (i, j=region1, region 2, ..., region 30, i} \neq \text{j)} \quad (2)$$

in which PAT_{jt} is the number of nanotechnology-related patents in region j in year t, and F_{jt} is the nano-funding received by region j in year t[5]. To construct the publication

[3] There are in total 31 inland provincial regions in China. Tibet is not included in the analysis due to lack of data.

[4] Nano patent is defined as a patent with a "nano" word in the title.

[5] The nano-patent collaboration data is not available, hence we use the collaboration extracted from nano-

weights in the above two equations we collected 164,000 nanotechnology-related publications from Thomson Reuters' Web of Science (WoS). The database is constructed based on an evolutionary lexical query searching and defining strategy developed by the Georgia Institute of Technology (see, for more details, Porter et al., 2008; Wang and Notten, 2010).

In addition to the collaboration weight above, we also use the geographical proximity between regions to construct a second set of spillover variables. The spatial proximity weight to capture spillovers from *i* to *j* can be expressed in three different ways depending on the different underlying assumptions (see also Vinciguerra, et al. 2011; Ertur et al., 2006; Wang, et al. 2013). First, if one assumes that spillovers from region *i* to region *j* is unaffected by spillovers going out from *i* to regions other than *j* and by spillovers coming into *j* from regions other than *i*, the spatial spillover weight can be directly expressed as:

$$w_{ij} = w_{ij}^{*} = 1/d_{ij}^{2} \quad \text{(i, j=region1, region 2, ..., region 30, i} \neq \text{j)} \qquad (3)$$

Here, d_{ij} is the geographical distance between regions *i* and *j*[6]. Secondly, one may assume that spillovers from region *i* to *j* may be affected by spillovers from *i* to regions other than *j*. In particular, if region *i* is geographically closer to the average region than to region *j*, there will be less spillovers flowing to region *j* compared to that to the average region. In this case the spillover weight from region *i* to *j* is defined as:

$$w_{ij} = w_{ij}^{*} / \sum_{j=1}^{30} w_{ij}^{*} \quad \text{(i, j=region1, region 2, ..., region 30, i} \neq \text{j)} \qquad (4)$$

This is often referred to as column standardization (see, Vinciguerra, et al. 2011).Thirdly, if one assumes that the absorptive capacity of region *j* is limited, the amount of spillovers *j* receives from *i* depends on the spillovers *j* receives from other regions. Thus, if *j* is more proximate to the average region than to *i*, it is expected to receive less spillovers from *i* than from the average region. The spillover weight from *i* to *j* in this case can be expressed as

$$w_{ij} = w_{ij}^{*} / \sum_{i=1}^{30} w_{ij}^{*} \quad \text{(j, i=region1, region 2, ..., region 30, i} \neq \text{j)} \qquad (5)$$

This is also referred as row standardization. We make use of all three sets of spillover weights for completeness.

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publication to create the interregional, as well as the international collaboration variable that is defined later.

[6] Distance between two provinces is measured as the distance between their capital cities, considering that a capital city is usually the central business and technology center of each province.

The spillover variables that capture the effect of proximity in generating spillovers can be derived as:

$$TECHSPILL_{it}^{spatial} = w_{ij} * PAT_{jt} \text{ (i, j=region1, region 2, ..., region 30, i} \neq \text{j)} \quad (6)$$

$$FUNDSPILL_{it}^{spatial} = w_{ij} * F_{jt} \text{ (i, j=region1, region 2, ..., region 30, i} \neq \text{j)} \quad (7)$$

Next, we construct an international collaboration intensity variable for capturing the effect of knowledge spillovers resulting from collaboration with foreign countries:

$$\mathrm{CI}_{\mathrm{it\_international}} = \frac{\sum \mathrm{PUB}_{\mathrm{ikt}}}{\mathrm{PUB}_{\mathrm{it}}} \text{ (k= country 1, country 2, ..., country27)[7]} \quad (8)$$

where $\mathrm{CI}_{\mathrm{it\_international}}$ represents the international collaboration intensity in nanotechnology-related publications of region *i* in year *t*, with $\mathrm{PUB}_{\mathrm{ikt}}$ being the number of co-authored nanotechnology-related publications involving region *i* and the foreign country *k* in year *t*, and $\mathrm{PUB}_{\mathrm{it}}$ the total number of nanotechnology-related publications stemming from region *i*. Each of the 27 foreign countries had at least 10 papers co-authored with an author based in China during the period of analysis[8]. These countries, in the order of the number of collaborative nano publications with Chinese regions are U.S.A., Hong Kong, Japan, Germany, Australia, Singapore, England, South Korea, Canada, France, Sweden, Taiwan, Switzerland, Spain, the Netherlands, Belgium, India, Russia, Ireland, Scotland, Pakistan, Norway, Portugal, Austria, Malaysia, Brazil, and Macao.

Finally, as control variables we include regional R&D intensity (ratio of total R&D to GDP), non-nano patenting productivity (ratio of non-nano patents to R&D), and per capita income. These variables take into account regional differences in, respectively, general scientific capability, general patenting propensity, and general economic prosperity.

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[7] This index is a sum of the collaboration intensity between region i and each foreign country. For instance, if region i collaborates with foreign country 1 and 2, this will be counted twice. Thus this calculation takes into consideration the number of foreign countries involved in one collaborated paper. Therefore, this intensity value is likely to be slightly higher than the one calculated by directly using the number of internationally collaborated papers with region i divided by the total publications of this region.

[8] Hong Kong, Taiwan and Macao have different S&T systems from mainland of China and don't receive R&D funding from Chinese government. Hence these regions are counted as "foreign" countries.

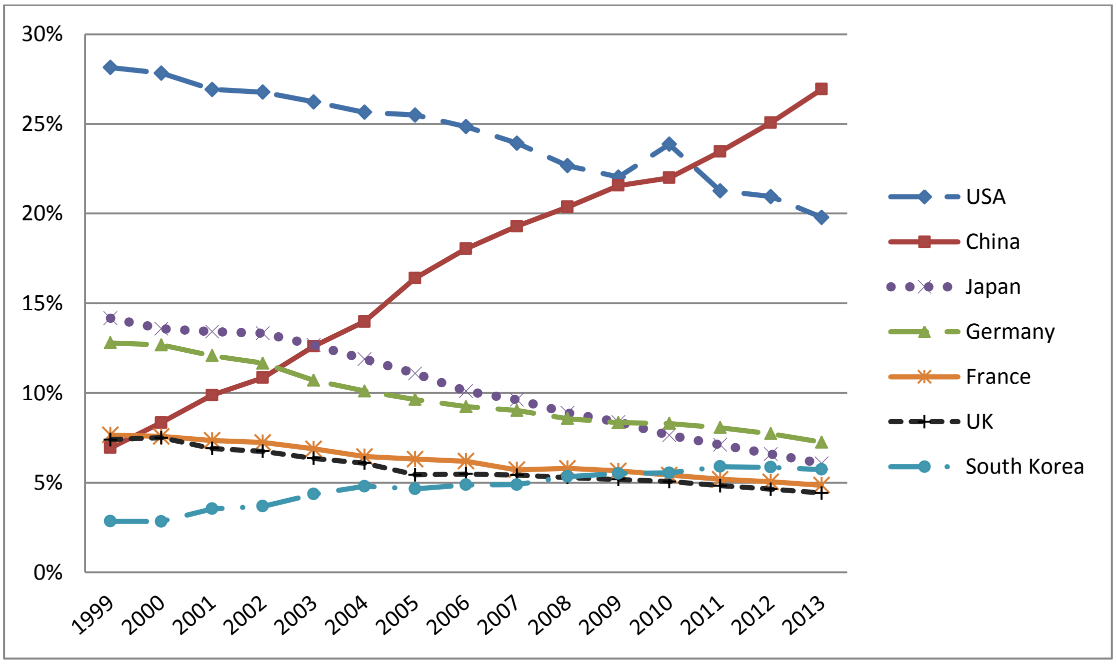
4. Empirical analysis and findings

In order to further set the stage for the econometric analysis, we first discuss some key aspects concerning the growth of nanotechnology across Chinese regions.

4.1 China's position in nanoscience and nanotechnology

The period 1999-2013 witnessed the number of nanotechnology-related publications with Chinese addresses growing from 2,487 to over 40,000, at an annual rate of 22 per cent. While the U.S. occupied a leading position in the early years of the emergence of nanoscience and nanotechnology, China has been able to catch up in an impressive way over the last decade (Figure 1). Between 1999 and 2013 as the share of China in global nano publications increased from 6.9% to 27%, that of most other leading players dropped—from 28% to 20% for the U.S., from 13% to 7% for Germany, from 14% to 6% for Japan, from 8% to 5% for France, and from 7% to 4% for the UK. Nanotechnology output (as measured by nanotechnology patents) too has been skyrocketing in China. According to the patent records at SIPO, the annual nano patent filing reached over 6,000 in 2010 from a meagre 98 in 1999.[9]

Figure 1: Share of top six countries in total nano-publications world-wide



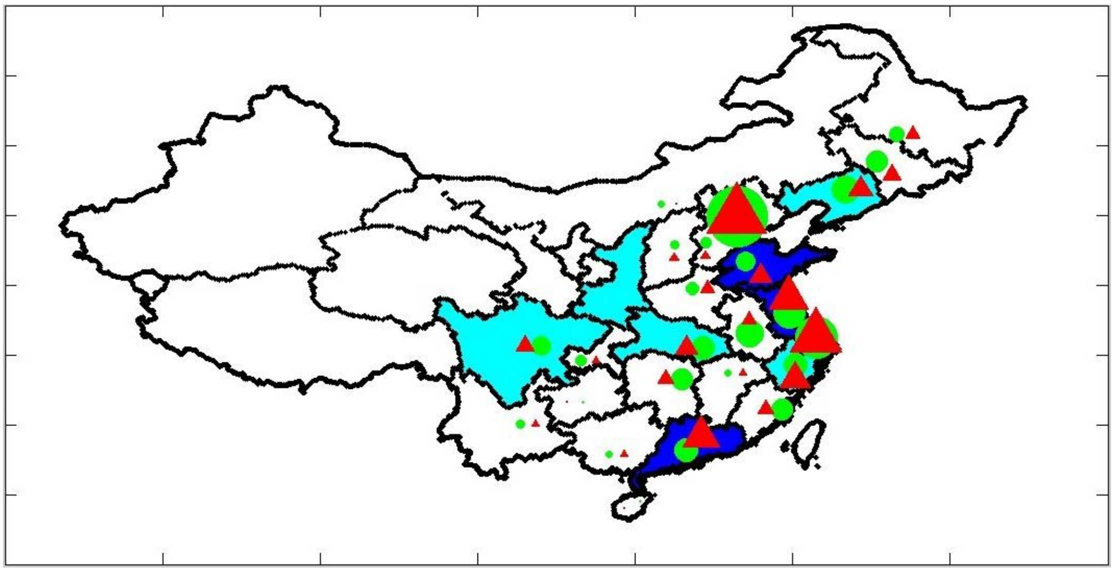
Source: Authors' own calculation based on the data collected from Web of Science.

[9] Chinese inventors, however, file for patents mainly locally in the Chinese patent office, with only fewer than 2 per cent of patent applications filed outside of China (Harvey, 2011). This makes it difficult to compare China's global position vis-à-vis other advanced countries.

4.2 Changing trends in regional disparity

As noted before, any discussion of overall growth of nanotechnology in China masks wide differences in scientific capabilities across Chinese regions. Figure 2 illustrates the strong regional disparities in nano funding, nano patenting and general R&D expenditure in China over the 2000-2010 period. With their very high R&D expenditures, coastal regions in Eastern China, and a few inland regions close to them, stand out compared to the rest of China. It is worthwhile to note that the regional disparity of nano funding is more pronounced than that of general R&D expenditure. As shown in Figure 2, the level of R&D expenditure in some central regions is reasonably high (see the light blue areas in the map). However, nano funding (green circles) and, nano patent applications (red triangles) have been concentrated in coastal regions. In nano patent applications, four regions (Beijing, Shanghai Jiangsu, and Guangdong) accounted for more than 50 per cent of the national total.

Figure 2: Distribution of nano patent application, nano funding and general R&D expenditure, 2000-2010



Note: 1) The map is based on the total value of each variable from 2000 to 2010. 2) Blue shades represent the general R&D expenditure (the darker the colour, the higher the value); Green circle is nano funding (the bigger the size the greater the value); Red triangle represents nano patent applications (the bigger the size the greater the value).

To further explore this, including econometrically as noted before, we divide Chinese regions into two categories: leading regions and lagging regions—the former category of regions are defined as those that fall into the top 25% in total scientific publications[10] during period of study; the rest of the regions represent the lagging category. A look at the trend in patent applications in the two categories of regions (Table 1) suggests an increasing dynamism in lagging regions. While leading regions witnessed a higher growth in nano patent applications during the first half of the period under study (1999-2004), the opposite happened during the later period (2005-2010).

Table 1: Number of patent applications and growth rates, by regional groups

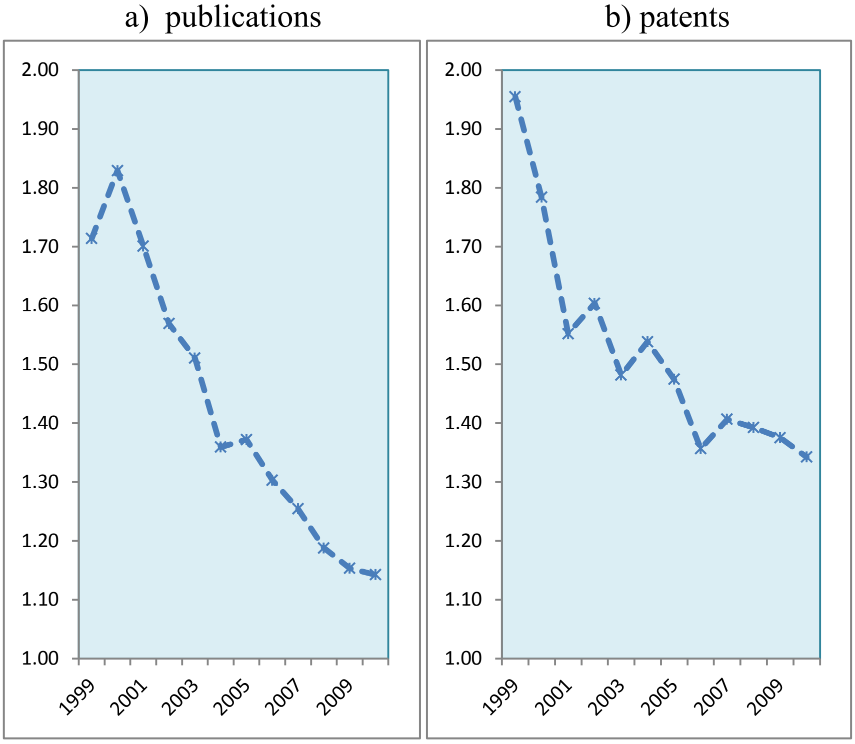
	number of patent applications			exponential growth rate	
Year	**2000**	**2005**	**2010**	**1999-04**	**2005-10**
Leading regions (Top 25%)	189	1704	4419	55%	21%
Lagging regions	86	692	1914	52%	23%

Source: Authors' own calculations based on patent data from SIPO.

Furthermore, we notice a sharp decline in the coefficient of variation in nanotechnology-related publications and patents between 1999 and 2010, respectively, from 1.71 to 1.14 and from 1.95 to 1.34 (Figure 3). These evidences indicate that scientifically lagging regions have increasingly become active in nanotechnology research, which need an explanation. In this respect, we highlight below the growing significance of inter-regional collaboration networks in China, especially involving lagging regions.

[10] Scientifically leading regions are Beijing, Shanghai, Jiangsu, Zhejiang, Shandong, Jilin, Guangdong, and Hubei.

Figure 3: Coefficient variation of regional nano-publications and patents



Source: Authors' own calculation.

Note: 1) Tibet is not included. 2) We removed one extreme outlier: 911 patent applications in 2001 were filed by a single person from Beijing. This caused Beijing to account for 85% of the national total that year.

4.3 Collaboration patterns in China

Table 2 documents the intensity of scientific collaborations (1) among Chinese regions, and (2) between Chinese regions and the rest of the world. The top part of table 2 reveals that international collaboration intensity in scientific publications for an average Chinese region was about 19% during 1999-2004, and about 17% during 2005-2009; leading regions, understandably, exhibited a slightly higher international collaboration intensity compared to lagging regions.

On the other hand, the bottom part of table 2 reveals that inter-regional collaboration intensity in scientific publications was much higher for both regional categories: it was close to 50% during the first period and increased by about nine percentage points during the second period. Even more interestingly, lagging regions on average had a much higher inter-regional collaboration intensity compared to leading regions.

Table 2: Collaboration intensity in nano-science

	1999-2004	2005-2010	comparison
	(1)	(2)	(3)=(2)-(1)
	international collaboration		
all regions	18.6	17.3	-1.3
leading regions	21.2	20.2	-1.0
lagging regions	17.6	16.2	-1.4
	national collaboration		
all regions	47.7	56.8	9.2
leading regions	37.2	39.0	1.8
lagging regions	53.6	64.8	11.1

Source: Scientific collaboration data are collected from Web of Science.

Note: Leading regions are defined as those that belonged to the top 25% in total scientific publications.

The collaboration intensity in lagging regions furthermore registered an 11 percentage point increase between the two periods (as against just a two percentage point increase in leading regions). In fact, during 2005-2010, approximately 65% of the scientific publications in an average lagging region were written with scientists based in another region. These observations lend credence to our suggestion earlier on that collaboration networks may be an important source of catching up in lagging regions—forging links with scientific communities in other Chinese regions could help lagging regions compensate for their weak scientific capabilities.

4.4 Results of the econometric analysis

As our dependent variable is the number of nanotechnology patents, a count data model such as Negative Binomial or Poisson is more appropriate than OLS. Chinese regions exhibit wide variations in patenting so the critical assumption of the equality of mean and variance of the Poisson model does not hold. Therefore we employ Negative Binomial Regression model as our preferred model. Given especially that regional patenting can be shaped by a host of other factors that we cannot fully account for, we employ a fixed effect model. We also include a full set of year dummies to account for unobserved annual events that may affect patenting in all regions. We experimented with all three sets of spatial proximity weights introduced in Section 3, and the results stay similar to each other. We report only the results based on the spatial proximity weight based on column standardization (Equation 4) – the most widely used spatial proximity weight. Results based on other weights are available upon request.

Summary statistics and correlation matrices for the total sample and the subsamples of the leading and lagging regions are reported in table 3. The average values of key variables display substantial differences across the two sets of regions. While the average nano funding is 5.13 billion Yuan (logarithmic values is 5.3), for China as a whole it is 13.2 (logarithmic value is 7.1) for the scientifically leading regions and 2.43 (logarithmic values is 4.7) for the lagging regions. Similarly, R&D expenditure spent in the leading regions is on average seven times as much as that in the lagging regions (77 versus 10 billion Yuan). Differences in GDP between the two sets of regions are somewhat lower however, with the average GDP being 462 and 146 billion Yuan for the leading and lagging regions respectively. Consequently, R&D/GDP in the leading regions is a little more than twice as much as that in the lagging regions. The correlation coefficient between *Nanotech spillovers* and *Funding spillovers* (via both collaboration and proximity) is rather high, so these two variables are employed in separate regression models.

Regression results are documented in table 4.[11] All models include the full set of controls and year dummies. We carry out three sets of analysis: for the full sample and for the subsamples of leading regions and lagging regions.[12] Models 1 to 3 present results based on the full sample with different combinations of the key explanatory variables. Results for leading regions are presented in models 4 to 6, and those for lagging regions in models 7 to 9.

[11] Regression results stay similar if we employ collaboration-based and proximity-based spillover variables in separate regressions. These results are available upon request.

[12] As noted before, leading regions are defined as those that belonged to the top 25% in total scientific publications. Different criteria of scientific capabilities such as nano publications, nano patents, and total patents yielded similar results as in table 4.

Table 3: Summary statistics and correlation matrices

		Mean	sd	min	max	Correlation matrix								
						1	2	3	4	5	6	7	8	9
	Full sample – all regions													
1	Nano funding (log)	5.32	2.40	0.00	9.70									
2	Nanotech spillovers -Collaboration (log)	2.43	1.43	0.00	6.08	0.86								
3	Nanotech spillovers - Proximity (log)	3.51	1.34	0.17	6.45	0.57	0.75							
4	Funding spillovers -Collaboration (log)	4.06	1.75	0.00	8.11	0.89	0.97	0.71						
5	Funding spillovers -Proximity (log)	5.32	1.34	1.12	8.81	0.57	0.72	0.96	0.72					
6	International collaboration intensity (log)	15.78	9.36	0.00	68.20	0.20	0.20	0.06	0.23	0.09				
7	R&D/GDP	1.08	1.09	0.11	7.41	0.53	0.56	0.31	0.53	0.30	0.21			
8	Non-nano patent/R&D	1.07	0.69	0.23	5.69	-0.36	-0.43	-0.41	-0.44	-0.44	0.00	-0.37		
9	GDP per capita	1.57	1.26	0.25	6.92	0.58	0.67	0.61	0.63	0.60	0.20	0.55	-0.14	
	Sub sample – leading regions													
1	Nano funding (log)	7.12	1.28	4.39	9.70									
2	Nanotech spillovers -Collaboration (log)	3.51	1.26	0.59	6.08	0.94								
3	Nanotech spillovers - Proximity (log)	3.99	1.34	0.57	6.38	0.72	0.82							
4	Funding spillovers -Collaboration (log)	5.39	1.19	2.52	8.11	0.94	0.97	0.79						
5	Funding spillovers -Proximity (log)	5.84	1.16	2.13	8.37	0.68	0.77	0.96	0.78					
6	International collaboration intensity (log)	19.42	5.44	0.00	35.70	0.12	-0.01	-0.16	0.00	-0.19				
7	R&D/GDP	1.85	1.68	0.23	7.41	0.66	0.54	0.18	0.53	0.13	0.21			
8	Non-nano patent/R&D	1.08	0.76	0.28	5.58	-0.37	-0.42	-0.14	-0.43	-0.15	0.20	-0.40		
9	GDP per capita	2.56	1.63	0.63	6.92	0.77	0.70	0.59	0.70	0.56	0.25	0.46	-0.08	
	Sub sample – lagging regions													
1	Nano funding (log)	4.67	2.38	0.00	8.27									
2	Nanotech spillovers -Collaboration (log)	2.04	1.27	0.00	4.58	0.82								
3	Nanotech spillovers - Proximity (log)	3.33	1.29	0.17	6.45	0.52	0.73							
4	Funding spillovers -Collaboration (log)	3.57	1.66	0.00	6.80	0.85	0.96	0.69						
5	Funding spillovers -Proximity (log)	5.13	1.35	1.12	8.81	0.52	0.70	0.96	0.70					
6	International collaboration intensity (log)	14.46	10.11	0.00	68.20	0.10	0.13	0.05	0.16	0.07				
7	R&D/GDP	0.80	0.56	0.11	2.98	0.52	0.53	0.38	0.51	0.40	0.15			
8	Non-nano patent/R&D	1.07	0.66	0.23	5.69	-0.44	-0.52	-0.55	-0.54	-0.56	-0.05	-0.53		
9	GDP per capita	1.21	0.85	0.25	6.12	0.47	0.55	0.64	0.53	0.65	0.08	0.40	-0.25	

Note: Year dummies are not reported.

Table 4: Results of negative binomial analysis on nanotechnology patent applications

	All regions			Leading regions			Lagging regions		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Log of Nano funding		0.061*	0.052		0.300**	0.314**		0.017	0.017
		(0.037)	(0.038)		(0.130)	(0.132)		(0.037)	(0.040)
Nanotech spillovers –Collaboration	0.267***	0.232***		-0.217	-0.249		0.431***	0.418***	
	(0.083)	(0.085)		(0.194)	(0.197)		(0.103)	(0.107)	
Nanotech spillovers – Proximity	-0.018	-0.036		-0.066	-0.063		0.085	0.079	
	(0.106)	(0.105)		(0.184)	(0.174)		(0.136)	(0.136)	
Funding spillovers –Collaboration			0.147**			-0.233			0.217**
			(0.074)			(0.163)			(0.091)
Funding spillovers –Proximity			0.097			-0.005			0.171
			(0.097)			(0.162)			(0.127)
International collaboration intensity	0.002	0.003	0.002	-0.005	-0.004	-0.004	0.001	0.002	0.001
	(0.004)	(0.004)	(0.004)	(0.009)	(0.009)	(0.009)	(0.004)	(0.004)	(0.004)
Control variables									
R&D/GDP	0.148***	0.138***	0.161***	0.257***	0.193***	0.171***	0.041	0.041	0.119
	(0.044)	(0.044)	(0.042)	(0.059)	(0.064)	(0.061)	(0.111)	(0.111)	(0.110)
Non-nano patent/R&D	0.065	0.078	0.098	0.181**	0.143*	0.137*	-0.105	-0.093	-0.018
	(0.062)	(0.061)	(0.060)	(0.079)	(0.079)	(0.081)	(0.107)	(0.110)	(0.111)
GDP per capita	0.014	0.018	0.029	0.132**	0.145***	0.137***	-0.041	-0.040	-0.016
	(0.034)	(0.034)	(0.033)	(0.053)	(0.052)	(0.051)	(0.067)	(0.067)	(0.064)
Constant	2.352***	2.105***	1.376**	4.353***	2.149	2.118	1.798**	1.734**	1.143
	(0.574)	(0.587)	(0.691)	(1.013)	(1.353)	(1.454)	(0.797)	(0.807)	(0.974)
Observations	330	330	330	88	88	88	242	242	242
Number of regions	30	30	30	8	8	8	22	22	22

Note: 1) Dependent variable is nano patent applications. 2) Explanatory variables are lagged by one year; 3) Year dummies are not reported. 4) *** at 1% significance level; ** at 5% significance level; and * at 10% significance level. 5) Leading regions are defined as those that belonged to the top 25% of all regions in total scientific publications.

4.4.1 Spillover effect: spatial spillovers v.s. collaboration spillovers

Model 1 consists of the two nanotechnology-patent spillover variables: in one spillovers stem from formal collaboration linkages and in the other they derive from geographic proximity. The results indicate that while formal collaborations generate knowledge spillovers, proximity has no significant effect. In model 2 we add the nano-funding variable, which has a significantly positive effect. In model 3, we replace the nanotechnology-patent spillover variables (proximity-induced and collaboration-induced) with nano-funding spillover variables. The results are similar: funding generates inter-regional spillovers through collaboration networks, but not through proximity.

In the subsamples of leading and lagging regions, results show that spillovers from other regions through collaborations exerted a significant positive impact in lagging regions (model 7, 8 and 9), but not in leading ones (model 4, 5 and 6). This applies for both nanotechnology-patent and nano-funding spillovers. These results are in line with our earlier discussion, demonstrating that collaboration linkages with other regions compensate for the weak capabilities of lagging regions and the low degree of government support they receive. Advanced regions, being the front runners of nanotechnology development, are able to capitalize on governmental support, leveraging their own capabilities.

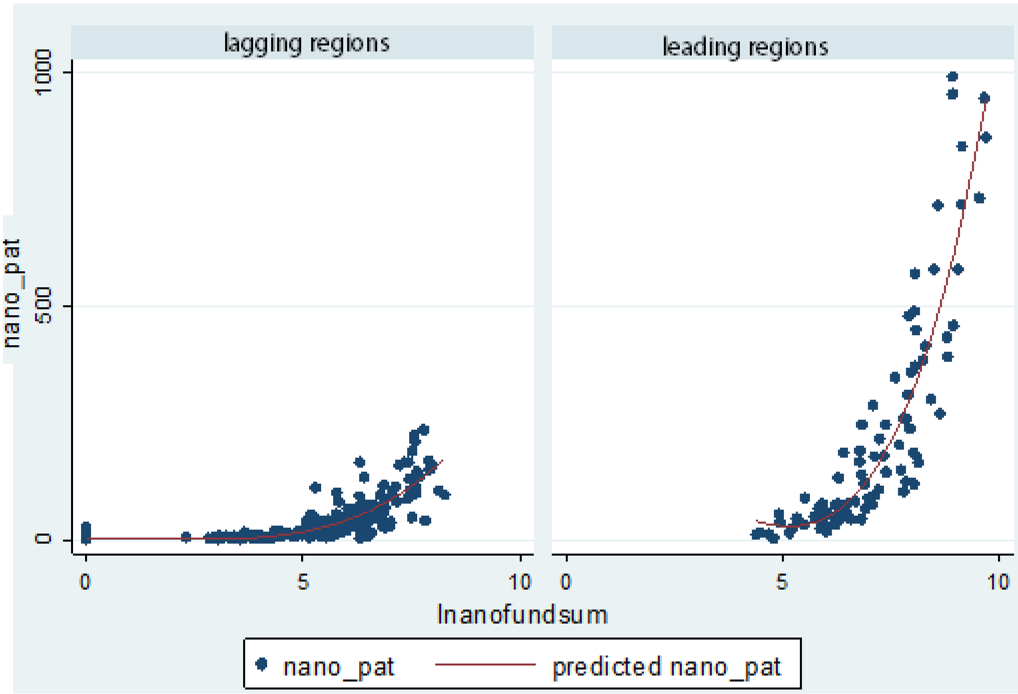
To further understand the nature of spillovers, we examined the sources of spillovers in leading and lagging regions. The results, which are not reported but are available upon request, indicate that while lagging regions received positive spillovers via collaborations with both leading and lagging regions, leading regions did not gain significant spillovers from collaborations with either set of regions. This indicates that the more involved are lagging regions in nanotechnology collaborations with other regions, the more technological knowledge they can gain from their partnering regions.

In contrast to spillovers via formal collaborations, those through spatial proximity are not statistically significant in the subsamples for both leading and lagging regions (models 4-9). This appears to suggest that informal communications or informal networks are not particularly strong even between geographically more proximate Chinese regions such as to generate knowledge spillovers among them. To reconcile these findings with the earlier literature that has found positive localized knowledge spillovers (Ponds, et al. 2010; Breschi and Lissoni, 2009), we may contend that even the most 'proximate' Chinese regions are too far to stimulate informal interactions between their respective scientific communities; the average geographical distance between Chinese regions – measured by the distance between capital cities – is around 2000 kilometres, which is far beyond the informal-spillover distance threshold suggested in the literature (e.g. Moreno,et al. 2003; Bottazzi and Peri, 2003).[13]

4.4.2 Funding effect

Comparison of the funding effect for the two categories (leading and lagging regions) reveals some interesting insights. First, direct funding has a significant positive effect on patenting only in leading regions (model 5 and 6), not in lagging regions (model 8 and 9). This is consistent with our earlier discussion in section 4.2 that advanced regions lead in both nano funding and nano patenting. Confirming this further, Figure 4 illustrates a substantially superior association between nano funding and nano patenting in leading regions compared to in lagging ones. This shows that regions with higher scientific capabilities (leading regions in Figure 4) received larger financial support from the Chinese state (13.2 billion yuan on average, with the mean of logarithmic values being 7.1), and consequently produced higher output (i.e. nano patent applications).

Figure 4: nano patent applications and nano funding



Note: 0 – lagging regions, 1 - leading regions. Leading regions are defined as those belonging to the

[13] Bottazzi and Peri (2003) find that spillovers are very localized and exist only within a distance of 300 kilometers, and Moreno et al. (2003) state that significant R&D spillovers take place in the range between 0 and 500 kilometers.

top 25% in total scientific publications.

4.4.3 International collaboration intensity

The international collaboration intensity variable shows little noticeable influence, with non-significant coefficients – negative for leading regions and positive for lagging regions. As indicated in Table 2, the international collaboration intensity on average is around 20 per cent in leading regions and 16 (or 17) per cent in lagging regions. It is difficult, however, to judge whether these are the optimum levels for knowledge production. Nevertheless, it is pertinent to note that Ozcan and Islam (2014), focusing on collaboration pattern in nanowire technology, point out that China has a relatively lower degree of international collaborative involvement compared to four other countries they studied: US., Japan, South Korea and France.

The lack of any significant impact of international collaboration supports the view that the surge of nano patent applications in China, in particular in its leading regions, was driven by China's indigenous capability rather than by international collaboration. More broadly, these results are in agreement with the notion that in the development of new technologies national linkages are likely to be more effective than international ones (Metcalfe and Ranlogan, 2008).

5. Conclusions

Over the past two decades, China has been attempting to make a giant leap in nanotechnology development. Given the country's strong scientific capabilities, as reflected in the presence of a number of world class universities and research institutes, already in the late 1990s China was projected to be a leader in emerging science-based technologies such as nanotechnology (Porter et al. 2002). True to these predictions, the country has fast emerged as a leading global player in nanotechnology. The evidence presented in this paper suggests that China's success in nanotechnology development in general owes in large part to the fostering of indigenous scientific capabilities through strong financial support from the state.

It is quite well known that economic development and scientific capabilities are highly uneven across Chinese regions, and our analysis revealed that the dynamics of nanotechnology development were quite different in regions with varying scientific capabilities. Thus, a few regions with superior scientific capabilities spearheaded the early growth of nanotechnology in China. However, regional inequalities in nanotechnology development are diminishing, with lagging regions making rapid strides in the development of this technology in recent years. In this context, we found that the key source of growth in nanotechnology patenting in lagging regions was the region-spanning collaborative ties that scientists from these regions forged. These collaborative ties generated significant inter-regional spillovers of nanotechnology knowledge. In leading regions, on the other hand, the growth of nanotechnology output stemmed principally from the government's financial assistance for nanotechnology-related R&D activities. Spillovers from other regions, or from abroad, played no significant role in the growth of nanotechnology in these regions.

Our study contributes to the catch up literature by highlighting on the one hand how targeted governmental support can help leading regions spearhead the growth of a new technology system, and on the other the role of region-spanning scientific collaborations in helping lagging regions partake in the development of these technologies. The study also contributes to the economic geography literature. The lack of proximity-induced spillovers via informal communications across Chinese regions – due to the vast distances between Chinese provinces – underscores the importance of formal collaborations for lagging regions to benefit from spillovers. We further hope that future studies in the economic geography tradition may place greater emphasis on the differences in growth dynamics in leading and lagging regions.

Our study raises some significant policy implications as well. Unlike in Europe, where European Union's research funding is geared to promote collaboration between European countries (Hoekman, et al. 2013), Chinese government's funding strategy is devoid of any serious measures to stimulate inter-regional collaboration. So far, the emphasis in the governmental funding guidelines has been limited to either international collaboration or industry-university collaboration. It may very well be the case that funding continues to flow also in the near future more into leading regions where scientific capacity is strong. While this is unavoidable on efficiency grounds, it is imperative that lagging regions are able to leverage and expand their scientists' ties in the broader scientific network within China and benefit from knowledge spillovers. As the catch up literature stresses, spillovers are a significant, historically proven mechanism to narrow technology gaps with leading regions. To ensure greater regional balance in technology development, Chinese government's funding strategy needs to incorporate measures to ensure scientific cooperation that spans regions. Such a strategy would be a natural extension of the current emphasis on university – industry collaboration, which, although we haven't been able to explicitly examine here, is well known to generate knowledge spillovers. As evidenced by our study in the context of an emerging technology like nanotechnology in which China is a frontrunner, and in the development of which state support has been a catalyst, cooperation among scientists and technologists can substitute for the relatively weak capabilities of some regions. Nurturing and expanding such networks through the right policies and incentives can play a vital role in helping today's lagging regions catch up in the production and use of new technologies thereby ensuring a more even pattern of regional development.

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