

State-led technological development : a case of China's nanotechnology development

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By Can Huang and Yilin Wu

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State-led Technological Development: A Case of China's Nanotechnology Development

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Abstract:

We analyze the nanotechnology patent applications filed in China from 1998 to 2008 and find that the extraordinary nanotechnology development in China has been primarily promoted by the public sector but not driven by industry and market force. This finding implies that developing countries such as China with public research capacity and commitment to technological development can make rapid progress in basic research of emerging technologies, but it remains uncertain whether and when local industry can benefit from public R&D investment to actively develop indigenous innovation.

Keywords:

Nanotechnology; Asia; China; R&D; Patent; State-led

JEL codes: O14, O33, O38

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We analyze the nanotechnology patent applications filed in China from 1998 to 2008 and find that the extraordinary nanotechnology development in China has been primarily promoted by the public sector but not driven by industry and market force. This finding implies that developing countries such as China with public research capacity and commitment to technological development can make rapid progress in basic research of emerging technologies, but it remains uncertain whether and when local industry can benefit from public R&D investment to actively develop indigenous innovation.

1. Introduction

As Noisi and Reid (2007) argued, large developing countries such as Brazil, China, and India with strong public research and development (R&D) sectors should be able to catch up and provide global leadership in emerging technologies such as biotechnology and nanotechnology. Indeed, after launching its national strategy to promote nanotechnology development in 2001 (Ministry of Science and Technology, 2001), China has devoted an increasing amount of R&D investment from government and industry to the field, produced a soaring number of scientific publications, expanded its postgraduate programs in related subjects, and established several new specialized institutions such as the National Center for Nanoscience and Technology in Beijing and the National Engineering Research Center for Nanotechnology in Shanghai. China finds itself increasingly well positioned to become a world leader in the field. However, it seems to be a long way from where China is now to such world leadership. Shapira and Wang (2009) interviewed Chinese nanotechnology policymakers, researchers, and business representatives and concluded that China's performance in nanotechnology patenting and product development is weak in comparison with its strength in research, indicating a significant gap between the research base and industrial development.

This article contributes to the literature that examines how developing countries can catch up in emerging technologies and analyzes the role governments can play in the catching-up process. Unlike many extant studies based on qualitative analyses, we performed rigorous quantitative analyses to assess the successes and difficulties of nanotechnology development in China. We searched and identified 30,863 nanotechnology patent applications in a comprehensive database, the China Patent Abstract Database, which includes over four million patent applications submitted to the Chinese Intellectual Property Office during the period of 1985–2009. We subsequently tested two competing hypotheses: (H1) Nanotechnology innovation in China is promoted primarily by the state and R&D activities are concentrated in public universities and research institutions; and (H2) Nanotechnology innovation in China has been responsive to market demand and produced by indigenous companies. By estimating a patent production function using data aggregated at the provincial level, we found consistent evidence to support the first hypothesis.

These results reveal that, contrary to what has happened in other developed economies, nanotechnology development in China has been dominated by R&D activities in universities and research institutions. China has yet to play a major role in the commercialization and application of nanotechnology, as its indigenous companies have not actively engaged in technological innovation and industrial development. Large developing countries such as China, with strong public research capacity and a tradition of committing to long-term technological development, can achieve rapid progress in research related to emerging technologies. The question remains, however, whether and when indigenous industries in those countries can benefit from government-led technological development plans to achieve competitiveness in the global arena.

From here on the paper is organized as follows. Section 2 reviews the literature on opportunities available to newcomers in technological catching-up and the role of government in promoting technological development. Section 3 examines the key strategy that the Chinese government adopted in the last decade to promote nanotechnology development and the progress that the country has achieved so far. Section 4 analyzes nanotechnology patent applications submitted to the Chinese Intellectual Property Office to test our hypothetical dilemma regarding whether nanotechnology development in China is promoted primarily by the public sector or by industry. Section 5 discusses the results and Section 6 concludes.

2. The role of governments in technological catching-up and reflection on nanotechnology development in China

Perez and Soete (1988) identified four entry barriers that latecomers must overcome if they are to catch up in a given industry: minimal fixed investment, scientific and technological knowledge, relevant skills and experience, and location advantages. Location advantages are positive externalities inherent to an environment in which latecomers plan to operate. Such advantages might involve proximity to equipment suppliers, sound transportation infrastructure, local availability of competent design as well as construction and engineering contractors, all of which can reduce the cost of production at a given location. Perez and Soete contended that entry barriers are lower in the new product introduction phase because any disadvantage developing economies might face regarding fixed investment and relevant skills and experience should be less challenging. They concluded that the best opportunity available to developing countries for catching-up lies in the new product introduction phase, especially if such countries can accumulate scientific and technological knowledge and location advantages relatively quickly.

The Chinese government's large investment in nanotechnology R&D and the correspondingly rapid growth in nanotechnology publications and patents suggest that China is overcoming the scientific and technological knowledge barrier. It may take quite a long time, however, for such public investment to pay off given the uncertainty of nanotechnology. Without funding, however, obsolescence is virtually guaranteed. After the US, Europe, Japan, and many other national and regional governments launched nanotechnology development strategies in the late 1990s and the beginning of the 2000s, Chinese policymakers felt that the country should jump on the bandwagon to avoid being left behind in exploring this emerging technology. It was thought by them that an earlier and firmer commitment to the technology would increase the likelihood that indigenous industry would be able to compete effectively when the technology matures.

Governments play an indispensable role in technological catching-up in East Asia by establishing public research institutions and universities and sponsoring the research carried out there. According to Lee (2000), the South Korean government established a series of government-funded research institutes in the 1960s and 1970s. The government did not demand an immediate return from these public research institutes, instead granting them full autonomy in allocating their operational funds. In addition to conducting contract research for industry and training R&D personnel, governmental research institutions attracted overseas scientists, many of whom played key roles in developing heavy and high-tech industries from the 1970s onward. Moreover, the existence of such public institutions enhanced the social status of scientists and engineers, attracting the best Korean students to study science and engineering.

East Asian governments also promoted public and private R&D consortia, which proved instrumental in absorbing and assimilating foreign technologies. Such R&D consortia reduced technological uncertainty by offering up-to-date information on technology trends and identifying appropriate targets for R&D projects (Lee and Lim, 2001; Lee et al., 2005). The governments also adopted measures to provide market protection, export subsidies, and government procurement practices favorable to domestic firms (Fransman, 1986; Sung and Carlsson, 2003). They even bargained with multinational enterprises over technological transfer and imposed domestic content requirements on foreign direct investment (Mu and Lee, 2005; Fan, 2006).

Hausmann and Rodrik (2003) argued in favor of a development strategy that incorporates private initiatives in a public action framework and encourages greater restructuring, diversification, and technological dynamism than market forces on their own would generate. Promoting such a “self-discovery” process, through which entrepreneurs could learn what they are good at producing at low cost, requires government support of entrepreneurship and investment in new activities *ex ante* while pushing out unproductive firms and sectors *ex post*. Hausmann and Rodrik demonstrated that *laissez-faire* policy would lead to under-provision of innovation while state planning and public investment can drive economic development. Similar to its counterpart governments in other East Asian countries, which played an instrumental role in the technological catching-up process, the Chinese government acted as the country’s largest source of R&D funding for nanotechnology development. Public investment was transformed into advanced infrastructure, equipment, instruments, and up-to-date technological standards. Government-funded research projects and positions attracted scientists and engineers, particularly young researchers, and retained them. Due to the government’s unprecedented efforts, China has emerged as a major global player in the field. In the next section, we summarize the progress of nanotechnology R&D in China over the last decade.

3. Progress of nanotechnology R&D in China

As Bai (2001, 2005) observed, when nanotechnology R&D techniques were introduced to China from abroad in the 1980s, they were well received by Chinese scientists. The Chinese Academy of Sciences, the National Natural Science Foundation and the State Science and Technology Commission (the predecessor of the Chinese Ministry of Science and Technology) started to fund related research. In the 1990s, several important academic conferences held in China, such as the 7th International Conference on Scanning Tunneling Microscopy (1993) and the 4th International Conference on Nanometer-Scale Science and Technology (1996), showcased Chinese scientists' early participation in the field. From 1990 to 2002, nearly 1,000 projects were funded by the Ministry of Science and Technology (or the State Science and Technology Commission). Over the same period, the National Natural Science Foundation of China approved another 1,000 small-scale grants for projects related to nanotechnology. In short, the initiation of nanotechnology R&D in China can be dated back to the 1980s and 1990s. Intensive R&D activities did not begin, however, until the early 2000s.

In November 2000, the National Steering Committee for Nanoscience and Nanotechnology was established to oversee national policies and coordinate action. The head of the Ministry of Science and Technology was the director of the committee. Vice directors included vice ministers in that ministry, the vice president of the Chinese Academy of Sciences, and the vice president of the National Natural Science Foundation. Officials from the Ministry of Education, the National Development and Reform Commission (a ministerial agency), and the Commission on Science, Technology and Industry for National Defense were also involved as members of the committee. The National Steering Committee for Nanoscience and Nanotechnology involved all the R&D

funding organizations in the country, making concerted policy action at the national level possible. The committee drafted the first Chinese national policy document intended to promote nanotechnology development, which was announced as the National Nanotechnology Development Strategy (2001–2010) and was reminiscent of similar strategies or initiatives announced in other countries, such as the National Nanotechnology Initiative in the US.

The National Nanotechnology Development Strategy (2001–2010)—hereafter “the Strategy”—emphasized the importance of basic science and called for strengthened financial support from the government. It prioritized commercializing nanotechnology and appropriating intellectual property from R&D activities. The Strategy argues that successful nanotechnology development depends on competent R&D personnel and highlights the need for training and retaining scientists in the field, which evinces a long-term view of policymaking. The Strategy mapped out a blueprint for Chinese nanotechnology development over the course of the following decade.

With guidance from the Strategy and early engagement in R&D, China’s global rise in nanotechnology has been phenomenal. In 1998, there were merely 1,875 nanotechnology-related scientific publications out of China, compared with 9,468 from the US and 4,423 from Japan.ⁱ In 2008, Chinese nanotechnology publications outnumbered those from Japan by a wide margin, positioning China in second place in the world in number of publications, trailing only the US. China’s share in the world’s nanotechnology publications was only 6 percent in 1998. By 2008, however, China accounted for 23 percent. Figure 1 lists the number of nanotechnology publications produced by the world’s 10 most-prolific countries from 1998 through 2008. A calculation of the average annual growth rate in the number of articles by the 10 most-prolific countries reveals rapid growth in China, South Korea, and India. China’s average annual growth

rate of 92 percent each year between 1998 and 2008 is nothing short of extraordinary. In contrast, the other countries in the top 10, including the US, Japan, Germany, France, the UK, Italy, and Russia, achieved only 8 to 15 percent rates in annual growth.

(Insert Figure 1 here)

China's progress is less impressive in patenting than in publishing. Using the PATSTAT database to count worldwide patent applications from 1929 through 2009 that fall under the European Patent Office's nanotechnology classification Y01N, we find that the 1,018 applications submitted by Chinese inventors or applicants accounted for only 0.88 percent of the world's total, in comparison with the US share of 34.2 percent and the Japanese share of 19.7 percent.ⁱⁱ Although China's share is very small, the number of patents filed by Chinese applicants grew rapidly, at an average rate of 36.8 percent per year, from 1998 through 2007 (Figure 2). Excepting South Korea, where the rate grew at an extraordinary 77.7 percent annually, applications in the rest of the top 10 countries increased more slowly than in China. Some leading countries, such as Japan and France, have seen negative rates of growth in nanotechnology patents. Nanotechnology patent applications filed with the Chinese Intellectual Property Office also grew rapidly during the same period. In 1998 there were merely 195 applications but the number increased to 4,491 in 2008.

(Insert Figure 2 here)

According to Lux Research (2008), the US and Japanese governments invested US\$1,816 million and US\$1,060 million (by purchasing power parity or PPP), respectively, on nanotechnology R&D during 2005–2007. The Chinese government invested US\$PPP893 million during the same

period, which positions China in third place in the worldwide ranking (Figure 3). However, corporate funding in China amounted to only US\$PPP348 million, which was only slightly more than one-third of government funding. Ranked by corporate funding, China was ranked fifth in the world after the US (US\$PPP2,362 million), Japan (US\$PPP2,038 million), Germany, and South Korea. A European Commission (2005) estimation showed that the Chinese government invested 83 million euros in 2004 on nanotechnology R&D, in comparison with the US government's 1.2 billion euros and the Japanese government's 750 million euros. China was thus ranked after the US, Japan, Germany, France, South Korea, and the UK in public investment in nanotechnology R&D in 2004.

(Insert Figure 3 here)

Indicators of scientific publications, patent applications, and public and corporate funding all reveal that China has been closing the gap with the leading countries in this emerging field in the past decade and is becoming a major player in the world.ⁱⁱⁱ This is attributed to the early launch of the Strategy and China's firm commitment to public funding of nanotechnology R&D. However, the literature suggests that although a lot of new technologies such as Internet emerged out of government-funded R&D projects, large-scale commercialization of those technologies depend on a variety of other factors in addition to public investment. The forerunner of the Internet, the ARPANET, was built up under the sponsorship of the US Department of Defense in the late 1960s. The US Department of Defense and the National Science Foundation's funding of computer science research and networking constituted the bulk of Internet-related R&D funding during the early period of technological development. Nevertheless, public investment alone cannot explain the US's lead in developing critical innovations and early adoption of new applications of the Internet. The neutrality of US public R&D programs regarding specific

commercial applications, the diversity of the federal R&D portfolio, antitrust and telecommunications policy, the venture capital industry, an open intellectual property rights regime, and pro-patent legislation in the late 1980s and 1990s have all contributed to the US's success (Mowery and Simcoe, 2002).

The ultimate goal of any development or technology strategy is to nurture industrial activities and foster business growth. The question remains whether indigenous Chinese industry has emerged robustly or picked up the momentum in nanotechnology R&D and industrial development. We argue that this is an important criterion for assessing the effectiveness of the Strategy. We therefore endeavored to investigate the emergence of nanotechnology development on the part of indigenous Chinese industry in light of an important fact: public investment is a necessary but not sufficient condition for successful development and commercialization of emerging technologies. In the following section, we use patent applications as indicators to represent technological innovations and test the two abovementioned hypotheses: (H1) Nanotechnology innovation in China is promoted primarily by the state and R&D activities are concentrated in public universities and research institutions; and (H2) Nanotechnology innovation in China has been responsive to market demand and produced by indigenous companies.

4. Drivers of nanotechnology patenting in China

4.1 Data

We collected information on nanotechnology patent applications filed in China from the China Patent Abstract Database. The database includes over four million patent applications submitted by domestic and foreign applicants to the Chinese Intellectual Property Office during the period

of 1985–2009. The information provided in the database on each patent includes patent application and publication number, application and publication date, patent number, title, International Patent Classification (IPC) class, abstract, claims, legal status, and so on. We used the same search strategy (Porter et al., 2008), which is applied to identify the worldwide nanotechnology publications, to find 30,863 nanotechnology patent applications in the Database. These applications have been filed by both domestic and foreign applicants. We were able to classify these applications according to applicants' origins at the country and provincial levels.

Statistics on these 30,863 nanotechnology patent applications shows that, although the first filing was in 1991, little momentum in nanotechnology patenting in China was built until 2001. The number of applications jumped from 526 in 2000 to 2,041 in 2001. In 2008 alone, 4,491 nanotechnology patent applications were submitted. Of these 30,863 patents, 93 percent are for inventions.^{iv} We observed two salient characteristics of nanotechnology patent applications in China. First, domestic organizations applied for proportionally more invention patents in nanotechnology than in other fields. Seventeen percent of the 30,863 patents were filed by foreign organizations while 83 percent were submitted by domestic organizations. Although the share in overall invention patent applications filed by domestic organizations increased steadily over the observation period of 1998–2008, by comparison only 67 percent of all invention patent applications in China were filed by domestic organizations in 2008. Second, universities and public research institutions dominated China's nanotechnology patent applications. As seen in Table 1, 56 percent of domestic nanotechnology patent applications were filed by such organizations. Industry accounted for only approximately 18 percent of domestic nanotechnology patent applications.^v In comparison, the share in domestic overall invention patent applications filed by industry was 49 percent in 2008, which had increased from 18 percent in 1998. University-industry and research institution–industry co-applications exist, but they account for

only about 3 percent of the total. In contrast, among applications filed by foreign organizations, 84 percent were filed by industry.

(Here Insert Table 1)

We used the OECD Technology Concordance (Johnson, 2002) to classify all nanotechnology patent applications into the International Standard Industrial Classification (ISIC) system. As seen in Figure 4, 43 percent of the applications were in the chemicals and chemical products sector and 19 percent were in the machinery and equipment sector. Three other sectors that account for more than one percent of all applications are radio, television, and communication equipment; precision and optical instruments and watches; and furniture and manufacturing not elsewhere included.

(Here insert Figure 4)

4.2 Model

In this section, we present our investigation of drivers of nanotechnology patenting in China by estimating a patent production model. The dependent variable is the count number of nanotechnology patent applications aggregated at the provincial level. We aggregated the data at the provincial level because the data pertaining to the key explanatory variables are harvested from various statistics yearbooks and are available only at the provincial level. Data on the dependent variable are all zero or positive integers, which indicates that a count data model is appropriate. We have data covering 30 provinces and a time span of 11 years (1998–2008). Simply pooling the data together in estimation would not have allowed us to control for unobservable heterogeneity. Therefore, we chose to proceed with fixed- and random-effects models. Because only 9.7 percent of the data are zero, we did not adopt the widely used Zero

Inflated Poisson model to control for the possible impact of the zero value. In other words, we did not model the difference between provinces that were not engaged in nanotechnology innovation and others that were engaged in innovation but failed to apply for patents.

After excluding the Zero Inflated Poisson model, we were left with fixed- and random-effects Poisson and Negative Binomial models. The Poisson estimator's efficiency relies on the assumption that the conditional mean is equal to the conditional variance (equidispersion), which is usually violated in practical applications, including in our case. With the over-dispersion of our data, the Poisson estimator would result in under-estimated standard errors and, accordingly, inflated statistical significance. The Negative Binomial model does not depend on the equidispersion assumption and thus is more flexible than the Poisson model for modeling over-dispersion. However, the maximum likelihood estimation of the Negative Binomial model is not consistent if there is any distributional misspecification. Wooldridge (1999) showed that, as long as the conditional mean is correctly specified, the fixed-effects Poisson estimator is consistent and a robust variance matrix for the estimator is obtainable.^{vi} In this sense, the Poisson estimator is more robust than the Negative Binomial model (Cameron and Trivedi, 1998, 2009). The robust standard errors of the Poisson model can also be obtained through the bootstrap method (Cameron and Trivedi, 2009). With robust standard errors, the assumption of equidispersion required with the Poisson model is relaxed. Bearing all these considerations in mind, we report the results of the Poisson model with robust standard errors together with those of the Negative Binomial model.^{vii}

The random-effects model assumes that the random effects (individual specific unobservables) are uncorrelated with regressors (individual specific observables). We have sufficient reason to

suspect this assumption in our case. For example, the quantity of patent applications is affected by the quality of the R&D personnel in the provinces, which is not measured by the regressors (we are able to measure only the quantity of the R&D personnel) and is accordingly included in the random effects. However, these random effects (e.g., the quality of R&D personnel) would be correlated with the number of scientific publications produced in the provinces, which is one of the regressors. If the assumption is violated as such, the random-effects estimator is not consistent. Unfortunately, we were not able to reject the random-effects Negative Binomial model with a Hausman test because the chi-square statistic is negative, which means that the model does not meet the asymptotic assumptions of the test. We were not able to perform the Hausman test on the Poission model either, because we used the bootstrap method to obtain the robust standard errors. We thus report the results of both the fixed-effects and random-effects models for the baseline model, but we focus on explaining the former. Regarding the results of the robustness check, we report only those of the fixed-effects models. Nevertheless, it is important to note that the results of the fixed-effects and random-effects model are not materially different.

4.3 Independent variables

To test the hypothesis H1, that China's nanotechnology development is promoted primarily by public universities and research institutions, we used scientific publications in the Web of Science database to measure research activities in Chinese universities and public research institutions. We were able to identify 112,524 nanotechnology publications authored by the Chinese organizations during the 1998–2008 period. We cleaned the addresses of the Chinese universities and institutions and assigned each publication to the respective provinces. Among these publications, we determined that only two percent (i.e., 2,396 articles) are published by industry or co-published by industry and university or public research institutions. The rest are written

solely by researchers in universities and research institutions. Therefore, we were able to consider the number of Web of Science publications as a precise measurement of research activities on the part of universities and research institutions in each province.

We constructed three variables to measure growth in the technology market, foreign direct investment, and high-technology industry in the provinces to test hypothesis H2, that China's nanotechnology development has been responsive to market demand and dominated by the activities of indigenous companies.

China promulgated the law of technology transfer in 1985. The law stipulates that technology transactions are exempt from any value-added tax as long as the contracts are verified by provincial bureaus of science and technology. Approved contracts are registered in the so-called technology market in provincial governments. They can be classified into contracts for commissioned technology development, technology transfer, consultancy, and service. According to Ministry of Science and Technology (2008) statistics, the registered transaction value of technology transfer contracts in China increased sixfold, from RMB43.6 billion in 1998 to RMB266.5 billion in 2008. The average annual growth rate of the transaction value over the period was nearly 20 percent. In 2008, the value of patent licensing contracts accounted for 9 percent of the total registered transaction value. Industry is the dominant player in the technology market. As technology transferor and recipient industry accounted, respectively, for 88 and 81 percent of total transaction value. We considered the transaction value of technology transfer contracts involving organizations in provinces as recipients as a proxy for demand for technology in a given province.

China has been the most popular foreign direct investment (FDI) destination among developing countries over the past three decades. After opening up its economy, China received US\$852.6 billion FDI from 1979 to 2008 (National Bureau of Statistics, 2009). In 2008 alone, China drew US\$108.3 billion of FDI inflow and was ranked second in the world in terms of volume of inflow after the US (UNCTAD, 2010). Hu and Jefferson (2009) studied the patenting activities of large and medium Chinese enterprises and found that China's integration into the world economy, manifested by the vast inflow of FDI, has expanded the technological opportunity for domestic firms to innovate and imitate. Hu and Jefferson showed that a 10-percent increase in the foreign share of industry value added results in an increase in patent applications on the part of both large and medium Chinese firms of approximately 15 percent. Hu (2010) argued that, as domestic firms' ability to imitate foreign technology gains strength and competition between foreign firms intensifies in the Chinese market, competitive threat forces foreign firms to file more patent applications in China. However, the positive impact of FDI on patenting activities in China was not confirmed by Yueh (2009). In her estimation of the patent production function at the provincial level, an exercise that is similar to ours, FDI is not a significant determinant of the patenting tendency of a province, even in the coastal region, which receives the majority of FDI inflow to China. For this study we used the accumulated FDI in each province as a proxy for foreign firms' activities. We wanted to investigate whether the continuous presence of foreign firms in the provinces would intensify their competition with domestic firms as well as competition between domestic firms—in which case the latter would file more nanotechnology patents—or alternatively whether foreign firms have sourced nanotechnology innovation from Chinese universities and research institutions and thus created market demand for nanotechnology R&D.

Nanotechnology has wide application in a broad spectrum of industries, particularly in pharmaceuticals, aircraft and aerospace, information and telecommunications, and medical equipment and measuring instruments, which are so-called high-technology sectors. Figure 4 demonstrates that nanotechnology patent applications in China are concentrated in these industries. Firms in high-tech industries spend proportionally more of their resources on R&D than do their counterparts in other industries. High-tech sectors in China developed rapidly over the past two decades. According to the National Bureau of Statistics (2009), high-tech industry revenue in China increased fivefold, from RMB1041.1 billion in 2000 to RMB5708.7 billion in 2008. Firms in these sectors employed 3.9 million employees in 2000, but, by 2008, they employed 9.45 million. We suspect that the rapid expansion of Chinese high-tech sectors has generated strong demand for nanotechnology development. To gauge the impact of this expansion, we include in the regression a variable representing high-tech sector revenues.

4.4 Control variables

There are two types of inputs regarding patent production: R&D investment and personnel. Because there are no consistent data available indicating R&D investment during the observation period, we had to rely on number of scientists and engineers working in natural science fields in universities and research institutions and scientists and engineers in large or medium enterprises as proxies for input into the patent production process.

China's patent law was promulgated in 1985 and amended in 1992, 2000 and 2008. The 2000 amendment was designed to harmonize China's intellectual property rights (IPR) standards with international rules, as China anticipated signing, in 2001, the Agreement of Trade-Related Aspects of Intellectual Property Rights as part of its World Trade Organization (WTO) obligations. The 2008 amendment aimed to enhance patent quality and better protect national

security and state interests. Since the patent law came into effect in 1985, the IPR protection environment in China had gradually improved, particularly after China joined the WTO in 2001. Following this, the number of patent applications in China increased rapidly, from 121,989 in 1998 to 828,328 in 2008. Among invention patent applications, the share of domestic applicants grew from 38 percent in 1998 to 67 percent in 2008. To control for the impact of improvements in the Chinese IPR system regarding nanotechnology patenting, we added number of invention patents of each province as a control variable.

4.5 Results

As seen in Table 2, the coefficients of number of Web of Science nanotechnology publications are highly significant in both the Negative Binomial and the Poisson model. In contrast, the coefficients of transaction value of technology transfer contracts involving organizations in a province as recipients are not statistically significant in either the Negative Binomial or the Poisson models. The coefficients of accumulated FDI are negative and significant. The coefficients of revenue in high-tech sectors are positive and significant in the Poisson model but not statistically significant in the Negative Binomial model.

Although the finding with regard to revenue in high-tech industries is inconclusive, the result provides evidence that nanotechnology patenting in China is highly correlated with academic research undertaken in university and public research institutions, but only weakly linked to technology demand, foreign direct investment, or the development of high-tech industries in the country. In other words, nanotechnology development in China is primarily driven by R&D activities carried out in the public sector, instead of by industry in response to market demand. The negative sign of the coefficient of FDI stock occurs because provinces with relatively greater FDI stocks do not exhibit more patents in nanotechnology. For example, Beijing is ranked 9th by

FDI stock among the 30 provinces, but is home to the most patents. Shanghai and Guangdong are ranked 2nd and 3rd by number of patent applications. However, the number of patent applications from Shanghai is twice of that of Guangdong even though Guangdong's FDI stock is almost twice that of Shanghai.

The coefficients of R&D human resources input in universities and large or medium enterprises are not statistically significant in most specifications. Surprisingly, the coefficient of number of scientists and engineers in research institutions is negative and significant across the models. This might be because of the transformation and consolidation of Chinese research institutions that took place after 1998. Many research institutions affiliated with ministries were transformed into for-profit enterprises, non-profit or intermediary organizations, or merged into universities (Huang et al, 2004). The number of public research institutions declined rapidly from 1999 to 2005. In 2001, research institutions employed 620 thousand people, while in 2005 they employed only 560 thousand (OECD, 2008). Our data also reflect this change, as in most provinces the number of scientists and engineers engaged in scientific and technological activities (natural science fields) decreased after 1998 and resumed growing only in 2007 and 2008. Because of its declining value, the coefficient of the variable is negative in the regression.

4.6 Robustness check

Although we could not find consistent data reflecting R&D investment in research institutions or in large or medium enterprises, we were able to find consistent data on university R&D expenditure during the observation period. We therefore replaced number of scientists and engineers with data on university R&D expenditure in the robust analysis. We also substituted number of scientists and engineers from large or medium enterprises with number of patent applications from large or medium enterprises, because the latter can also be used to measure the

intensity of innovation activities in industry. Alternatively, we could have used gross R&D expenditure in each province in the patent production function instead of measuring R&D input from universities, research institutions, and industry separately. Through this specification, we were able to reduce the possible impact of multicollinearity between the key independent variables and control variables. We also substituted the transaction value of technology transfer contracts involving organizations in provinces as recipients and transferors with the variable considering only organizations as recipients. We then were able to control for cases in which universities and research institutions in one province license a high volume of patents to companies in another province, which would otherwise not be counted in the baseline model. None of the abovementioned robust analyses renders materially different results compared with those of the baseline model (see Table 3). In particular, the coefficients of revenue in high-tech sectors are either not significant or are negative and significant in robustness check results. The results of the random-effects Negative Binomial and Poisson models are similar to those of the fixed-effects models and are available upon request from the authors.

(Here insert Table 3)

5. Discussion

The econometric analysis supports the first hypothesis, namely that nanotechnology patenting in China is highly correlated with academic research undertaken in university and public research institutions, but weakly linked to technology demand, foreign direct investment, and the development of high-tech industries in the country. This confirms the observation that China has successfully boosted basic nanotechnology research, but has not yet performed extraordinarily well regarding industrial development.

Chinese industrial R&D in nanotechnology has remained weak. Corporate funding in China was at a level that was only 40 percent of the level of government funding during the period of 2005–2007 (Figure 3). In contrast, industry in general accounted for 72.3 percent of total Chinese R&D expenditure in 2007 (Ministry of Science and Technology, 2009). Differing from what has occurred in China, corporate funding by American and Japanese enterprises has far surpassed government funding, arguably because firms from these two countries have acquired or developed advanced technological capabilities that allow them to appropriate sufficient return on R&D investment. Bai (2005) estimated that only about 300 firms in China engaged in business activities related to nanotechnology in 2005. The majority of indigenous Chinese firms have not established a high level of international competitiveness based on technological advancement, innovation, or R&D. It has been easier for them to purchase advanced production lines or blueprints from domestic or foreign suppliers and leverage their low-cost manufacturing capability to compete domestically or internationally. Seeking to transfer cutting-edge technologies from universities and research institutions is costly and risky. There thus are not enough incentives on the demand side for Chinese firms to engage in nanotechnology R&D.

In addition, among domestically generated nanotechnology patent applications in China, 56 percent were filed by universities and research institutes. Only 18 percent were applied for by industry representatives (Table 1), whereas in other industrialized countries industry is the main performer of industrial development and the leading source of patent applications. For example, US universities and research organizations were granted over 1,000 nanotechnology patents in the period of 1990–2006, while industry produced about 5,000 patents during the same period (Shapira and Wang, 2009). Most indigenous Chinese companies have lacked sufficiently robust technological capabilities with which to fully assess prototype technology developed in public research institutions and universities. Such organizations were established to profit from their

core technologies and have no long-term research agenda. In addition to seeking a modest amount of technological advice and using some university-owned equipment and facilities, these companies did not interact to a significant extent with universities or research institutions.

Based on data collected from interviews with nanotechnology scientists and company representatives, Shapira and Wang argued that scholars in the Chinese Academy of Science as well as those from universities were incentivized to apply for patents because patent applications as well as publications were important elements in career development and promotion, and also for meeting the deliverable targets of their government-funded research projects. Many of these patents are never used after being granted. In a survey jointly undertaken by the Chinese Intellectual Property Rights Office and the Ministry of Education in 2005, canvassing the top 100 Chinese universities in patenting activities, 24 among the 50 universities responding to the survey indicated that researchers have no interest in using or licensing patents because their primary objective is to attain patents instead of using them to appropriate return on R&D investments (Liu, et al. 2007). The survey also revealed that the monetary compensation scientists receive for patent grants in the 50 universities is greater than the compensation they receive for scientific publications.

It is perhaps tempting to think that indigenous Chinese firms have not yet patented more actively because it can take more than a decade to benefit from intensive public R&D investment. We argue that this is not the case. The US and China started at almost the same time to invest heavily in public funding of nanotechnology development. As noted above, US firms were granted five times more patents than US universities and research institutions were from 1990 to 2006. However, Chinese firms accounted for only 18 percent of all nanotechnology patent applications

during the period of 1998–2008. Weak R&D capabilities and tenuous connections with university and research institutions is the culprit behind the sluggish patenting performance of indigenous industry in China. One might interpret the high correlation between publications and patent applications as characteristic of a close relationship between basic and applied research in nanotechnology in China. Such an interpretation would be valid, however, only if the majority of Chinese nanotechnology patents were produced by industry, which is not true. We argue that the high correlation between the production of publications and patents at the provincial level is because that not only the majority of publications but also over 50 percent of all patents are generated by universities and research institutions.

Darby and Zucker (2003, 2005) found that U.S. firms become involved in nanotechnology wherever and whenever scientists publish breakthrough academic articles. They argued that the commercialization of nanotechnology depends on the occurrence of scientific research and discoveries in the same US regions. In contrast to the situation in the US, academic research and industrial development and production in China are performed in disparate locations with only loose links connecting them. As seen in Table 4, Beijing, the capital city in the north, hosted 22 percent of the departments or institutions that published more than 50 nanotechnology Web of Science publications and filed 21 percent of the country's patent applications. However, Beijing hosted only 6 percent of the listed companies that engage in business activities related to nanotechnology.^{viii} Controlling for the share in general listed companies from Beijing in China's total listed companies (8 percent), we confirm that 6 percent is actually smaller than what would be expected if nanotechnology-related business activities were distributed equally across the country. Beijing is a center of academic research and patenting activities, but not a hotspot of industrial development and production.

(Insert Table 4 here)

Guangdong in Southern China is, by contrast, home to merely 2 percent of departments or institutions that have published more than 50 nanotechnology articles or applied for 8 percent of patents, but it hosted 12 percent of the listed companies engaging in nanotechnology-related business. By no means is Guangdong an academic research center, but it is an important location for industrial applications. Much like Guangdong, Zhejiang accounted for a small share in basic research and patent applications, but concentrated a significant share in industrial activities. Beijing, Guangdong, Zhejiang, Jiangsu, and Shanghai, plus Tianjin, are the six most highly developed provinces in China in terms of GDP per capita and all are known for having sound infrastructure, an open business environment, abundant financial resources, and a concentration of human resources. There is no other reason to explain the conspicuous differences in their respective performances in nanotechnology R&D and related business activities other than that basic research, technology development, and industrial production of nanotechnology in China are carried out separately. An increasing proportion of public funding has been poured into universities and research institutions affiliated with the Chinese Academy of Sciences, which are largely concentrated in Beijing and Shanghai (Beijing, Shanghai, and Hong Kong alone produced almost half of all Chinese nanotechnology publications). Such public R&D investment has resulted in a boom in scientific publications and patent applications in some locations. However, the commercialization of technology has been weak, and industrial development and production have remained detached from the scientific research system.

6. Conclusion

China has made tremendous progress in nanotechnology development since the National Nanotechnology Development Strategy was enacted in 2001. Intensive public investment in nanotechnology R&D in China over the past decade has paid off to a certain degree, as China has produced the second-largest number of scientific publications in the world since 2003, trailing only the US. In this study, we estimated a patent production function on the basis of the nanotechnology patent applications submitted to China's Intellectual Property Office during 1998–2008, to confirm a hypothesis that nanotechnology innovation in China has so far been promoted primarily by public universities and research institutions, not by industry. Indigenous Chinese companies have remained weak in patenting activities. This finding reveals that, in the early stage of technological development, a developing country such as China is able, through large-scale public R&D investment, to engage actively in research related to emerging technologies and contribute new knowledge and technology to the international scientific community. However, unlike their counterparts in developed economies, indigenous companies in developing countries are handicapped by their weak R&D capabilities and their loose connections with university and research institutions. They may have difficulty in benefiting from R&D activities, which are largely concentrated in the public sector, at least in the short run. Public R&D investment is therefore a necessary but not sufficient condition for enabling developing countries to promote emerging technologies. The capabilities of indigenous companies, policies promoting competitiveness, regulatory frameworks, the venture capital industry, intellectual property rights regimes, and corporate practice all play roles. The take-off of indigenous companies in the fields of emerging technologies demands more nuanced policies to facilitate spillover from public R&D and synergy between the academy and industry. That is the challenge for industrial policy in developing countries.

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Table 1: Nanotechnology patent applications filed in the Chinese Intellectual Property Office (1985–2008, Percentage)

Applicant	From domestic organizations	From foreign organizations
University	43.28	5.85
Research institutions	13.28	3.95
Industry	18.00	83.73
Individual	21.46	2.57
University-Research institutions	0.25	0.17
University-Industry	2.97	1.85
Research Institution-Industry	0.34	0.83
University-Research institution-industry	0.02	0.02
University-Individual	0.14	0.04
Research institution-Individual	0.03	0.02
Industry-Individual	0.24	0.96
Total	100	100

Table 2: Nanotechnology patent production function (all explanatory variables are transformed into logarithm values)

	Dependent variable: Number of nanotechnology patent applications				
	Negative Binomial model, fixed effects	Negative Binomial model, random effects	Poisson model, fixed effects, robust standard errors obtained by xtpqml	Poisson model, fixed effects, robust standard errors obtained by bootstrap	Poisson model, random effects, robust standard errors obtained by bootstrap
Number of scientists and engineers in universities engaged in S&T activities (natural science fields)	.14(.12)	.23(.12)*	.42(.32)	.42(.33)	.46(.32)
Number of scientists and engineers in research institutions engaged in S&T activities (natural science fields)	-1.3(.12)***	-1.1(.12)***	-1.9(.32)***	-1.9(.36)***	-1.8(.37)***
Number of scientists and engineers in large or medium enterprises engaged in S&T activities	.07(.10)*	.011(.095)	.076(.25)	.076(.29)	.033(.28)
Number of invention patents	.58(.090)***	.55(.086)***	.49(.14)***	.49(.16)***	.48(.15)***
Number of Web of Science nanotechnology publications	.69(.074)***	.65(.070)***	.52(.12)***	.52(.14)***	.54(.14)***
Transaction value of the technology transfer contracts involving organizations in provinces as recipients	-.061(.075)	-.056(.074)	-.083(.10)	-.083(.12)	-.088(.12)
Accumulated foreign direct investment (FDI stock)	-.40(.11)***	-.31(.10)***	-.25(.14)*	-.25(.15)	-.26(.15)*
Revenue of high-tech sectors	.12(.11)	.15(.10)	.50(.26)**	.50(.29)*	.50(.28)*
Number of observations	330	330	330	330	330
Number of groups	30	30	30	30	30

Note: The data between the parentheses are standard deviations. *** denotes significance at the 1% level, ** denotes significance at the 5% level, * denotes significance at the 10% level.

Table 3: Robustness check (All explanatory variables are transformed into logarithm values)

	Dependent variable: Number of nanotechnology patent applications			
	Negative Binomial model, fixed effects	Poisson model, fixed effects, robust standard errors obtained by bootstrap	Negative Binomial model, fixed effects	Poisson model, fixed effects, robust standard errors obtained by bootstrap
R&D expenditure of universities (natural science fields)	.25(.095)***	.11(.17)	-	-
Number of scientists and engineers in research institutions engaged in S&T activities (natural science fields)	-1.2(.11)***	-1.8(.25)***	-	-
Number of patent applications by large or medium enterprises	-.0039(.070)	.0033(.13)	-	-
Gross R&D expenditure	-	-	.36(.16)**	.32(.32)
Number of invention patents	.61(.10)***	.49(.19)***	.68(.099)***	.27(.11)**
Number of Web of Science nanotechnology publications	.55(.092)***	.46(.18)***	.37(.091)***	.55(.23)**
Transaction value of the technology transfer contracts involving organizations in provinces as recipients and transferors	-.066(.052)	-.060(.11)	-.29(.090)***	-.16(.15)
Accumulated foreign direct investment (FDI stock)	-.36(.11)***	-.24(.16)	-.32(.12)**	-.57(.23)**
Revenue of high-tech sectors	.063(.11)	.46(.27)*	-.22(.13)*	.35(.28)
Number of observations	330	330	330	330
Number of groups	30	30	30	30

Note: The data between the parentheses are standard deviations. *** denotes significance at the 1% level, ** denotes significance at the 5% level, * denotes significance at the 10% level.

Table 4: Geographical Mismatch of China’s Nanotechnology Academic Research Centers, Patent Application and Commercialization Hotspots

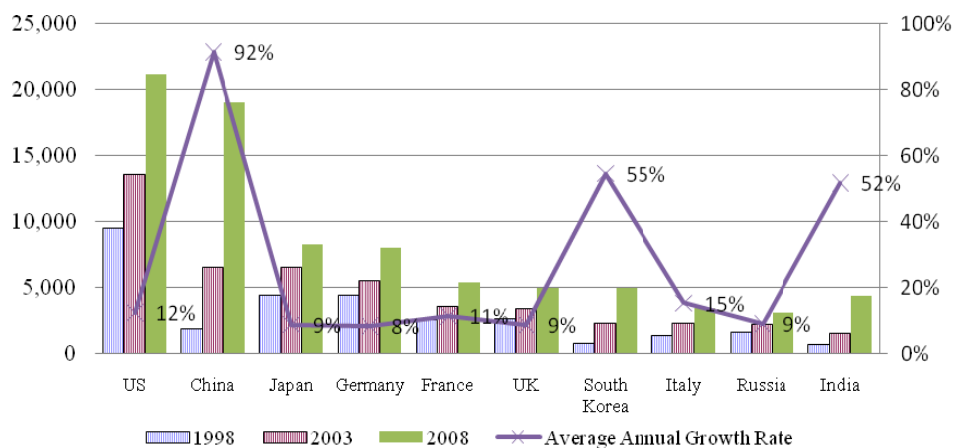
Provinces	Number of departments or institutions with more than 50 nanotechnology publications (percentage of national total)	Number of nanotechnology patent applications submitted to the Chinese Intellectual Property Office (percentage of domestic organizations’ total)	Number of listed nanotechnology companies (percentage of national total)	Number of general listed companies (percentage of national total)
Beijing	58 (22%)	5254 (21%)	10 (6%)	135 (8%)
Guangdong	5 (2%)	2094 (8%)	19 (12%)	240 (14%)
Jiangsu	16 (6%)	1973 (8%)	15 (10%)	129 (7%)
Shanghai	37 (14%)	4163 (17%)	19 (12%)	159 (9%)
Zhejiang	6 (2%)	1585 (6%)	15 (10%)	143 (8%)
National total	261 (100%)	24885 (100%)	157 (100%)	1751 (100%)

Source: Authors’ own calculation.

Note:

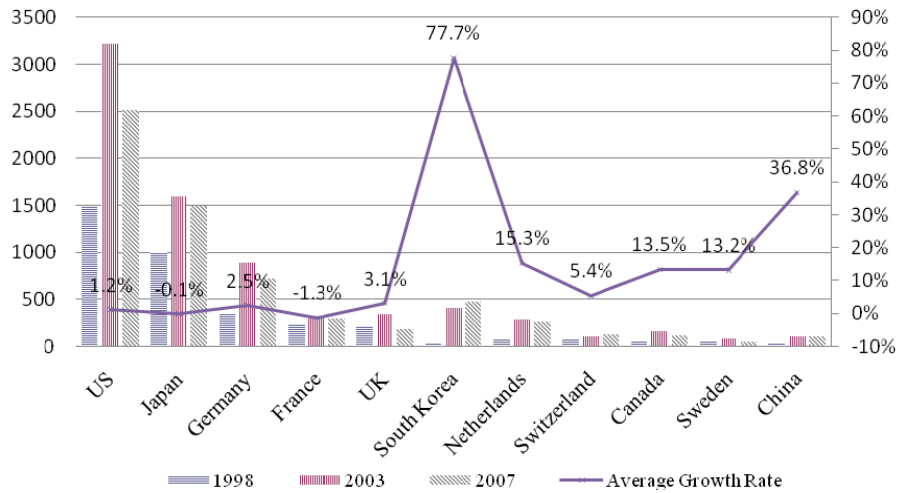
1. The listed nanotechnology companies are listed firms that have declared that they engage in business activities related to the technology in their annual reports. Annual reports of the Chinese listed companies are sourced from the China Infobank database.

Figure 1: The World’s 10 Most Prolific Countries in the Nanotechnology Field: 1998–2008



Data source: MERIT Database of Worldwide Nanotechnology Scientific Publications. Authors’ own calculation.

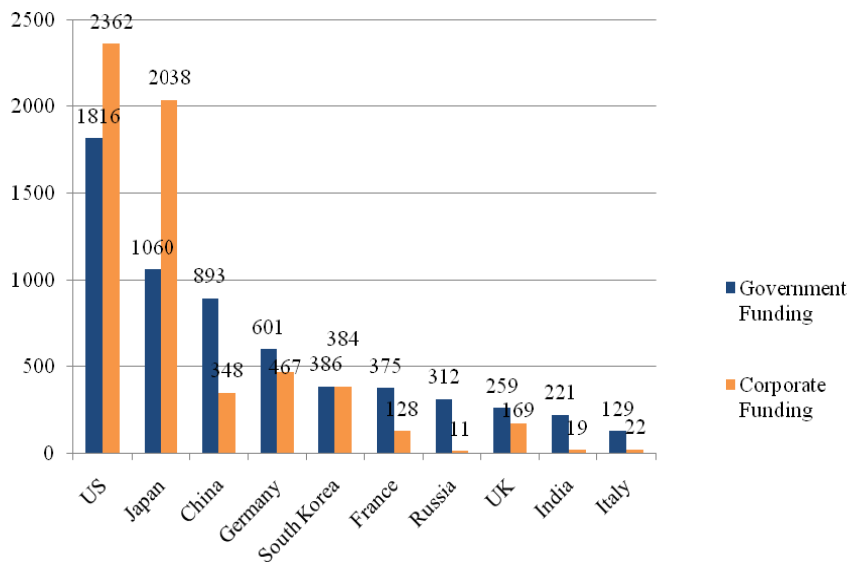
Figure 2: The Top 10 Countries and China (13th) in terms of Nanotechnology Patent Applications: 1998–2007



Data source: PATSTAT database (September 2009 version). Authors' own calculation.

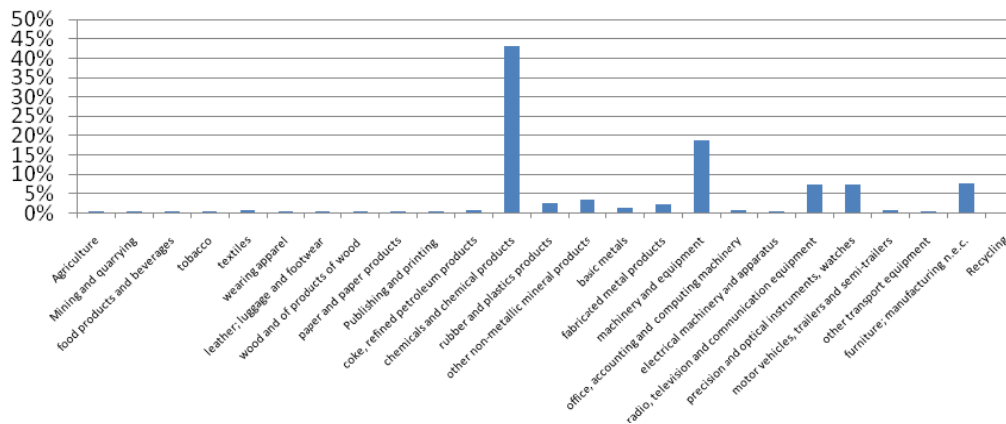
Note: Nanotechnology patents are defined as such in accordance with the European Patent Office's nanotechnology Y01N classification.

Figure 3: Estimated Government and Corporate Nanotechnology Funding (PPP US\$ Million), 2005–2007



Source: Lux Research (2008).

Figure 4: Share of Nanotechnology Patent Applications from Each Two-digit Industry



ⁱ The analysis of scientific publications in this article is based on the MERIT Database of Worldwide Nanotechnology Scientific Publications. It is composed of scientific publications indexed by the Web of Science. The search strategy used to define nanotechnology publications was developed by the Georgia Institute of Technology and described in Porter et al. (2008). Huang et al. (2011) compared this search strategy and other popular strategies and found that the analytical results obtained by this strategy are robust.

ⁱⁱ The version of the PATSTAT database is that of September, 2009. We used the PATSTAT database here because it includes information regarding worldwide patent applications and provides a level ground for international comparisons. The classification code Y01N is attached to a patent application when the patent examiner at the European Patent Office considers it to be related to nanotechnology. Using the Y01N classification is a more rigorous way of identifying nanotechnology patents than using a keyword search, because the examiners ensure that patent applications with the Y01N classification are nanotechnology-related. In contrast, many applications with nanotechnology in the title or abstracts which would be identified by a keyword search are not directly related to nanotechnology. Applicants use the term just because it is a buzzword. Therefore, we may identify fewer nanotechnology-related patents through the Y01N classification than through a keyword search. A discussion of this issue and detailed introduction of the Y01N classification is provided by Scheu et al. (2006).

ⁱⁱⁱ So far we have presented only counts of nanotechnology publications and patent applications. Huang and Wu (2010) developed a citation score to measure the impact or quality of Chinese nanotechnology publications. China was ranked 35th in the world by citation score in 1998. Its ranking had improved to 23rd by 2002 but dropped to 27th in 2006, well behind the most advanced countries. Most Chinese universities score much higher when ranked by number of nanotechnology publications than by citation scores. It is well known, however, that citation is only one proxy among others to indicate the quality of a publication. In addition, citation is affected by multiple factors other than quality of publication, such as the size and extent of a relevant network of scholars and the openness of a national innovation system. Because the China Patent Abstract Database does not provide information regarding patent citations, we were not able to construct an indicator to measure the quality of Chinese nanotechnology patents through citations.

^{iv} There are three types of patents in the Chinese patent system: inventions, utility models and designs. Invention patent applications are subject to substantive examination. Patent examiners need to conduct a search of prior art before granting invention patents. Utility model patents, which usually represent incremental technological improvements, are granted on a registration basis and need not go through a substantive examination process. Invention patents are protected for 20 years. However, utility model patents are protected for only 10 years.

^v The share of individuals among domestic applicants for Chinese nanotechnology patents is 21.5 percent. This is much higher than the share of individuals among foreign applicants, which is 2.6 percent. Such a large share of patents being applied for by individuals is characteristics of patenting activities in China. In 2009, 25 percent of all domestic invention patents were applied for by individuals.

^{vi} We used the Stata user-written program `xtpqml` to obtain the robust standard errors of the fixed-effects Poisson model, as suggested by Wooldridge (1999).

^{vii} An exposition of the Poisson and Negative Binomial panel model is provided in Stata (2007).

^{viii} Analysis of nanotechnology-related business activities is performed only on listed companies. There is no statistical information available regarding nanotechnology start-ups or small or medium enterprises in China, although they are considered to be important in commercializing new technologies as well.

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